MARS15: Basics and New Features

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MARS15 Mini-Tutorial
Fermilab
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OUTLINE (1)

- Introduction and Basics
- New Inclusive, Exclusive and Hybrid Mode Control
- Improved Tagging, Nuclide Treatment (DeTra),DPA
- Six Geometry Options with new ROOT one
- GUI, Tallies, I/O, Histograming, Combining Runs
- MAD-MARS Beam-Line Builder
- MARS-ILCroot Link
- A Couple of Recent Applications

OUTLINE (2)

- DeTra Use and Residual Dose from Small Objects (by Vitaly Pronskikh)
- ROOT: New Geometry Option in MARS15 (by Igor Tropin)
- Q&A During and After Presentations

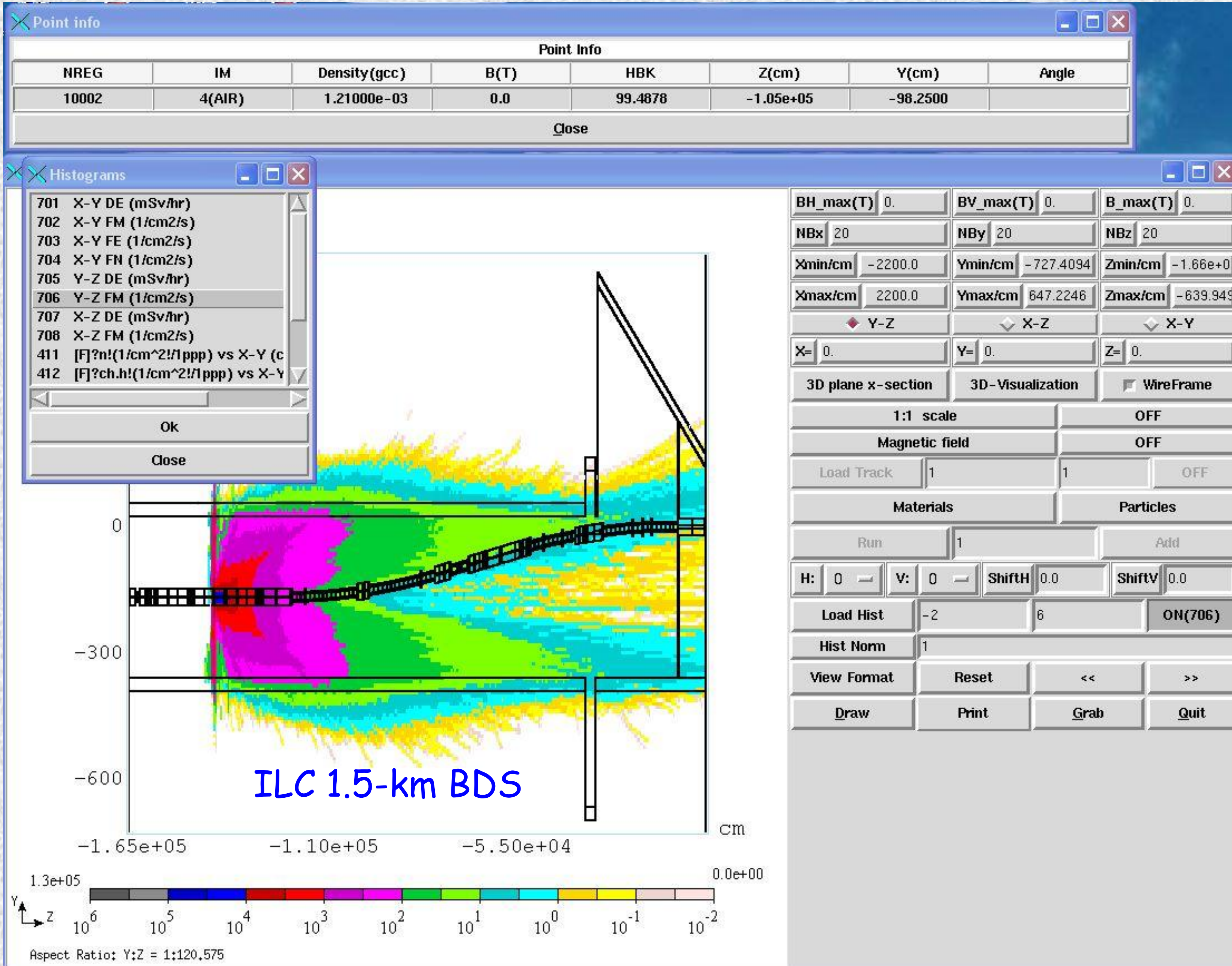
MARS Code System

The MARS code system is a set of Monte Carlo programs for detailed simulation of hadronic and electromagnetic cascades in an arbitrary 3-D geometry of shielding, accelerator, detector and spacecraft components with energy ranging from a fraction of an electronvolt up to 100 TeV. It has been developed since 1974 at IHEP, SSCL and Fermilab

Current MARS15 combines well established theoretical models for strong, weak and electromagnetic interactions of hadrons, heavy ions and leptons with a system which can contain up to 10^5 objects, ranging in dimensions from microns to hundreds kilometers in same setup

300 official users worldwide; tutorials

http://www-ap.fnal.gov/MARS/


Point info
Point Info
NREG | IM | Density(gcc) | B(T) | HBK | Z(cm) | Y(cm) | Angle
10002 | 4(AIR) | 1.21000e-03 | 0.0 | 99.4878 | -1.05e+05 | -98.2500
Close
Histograms
701 X-Y DE (mSv/hr)
702 X-Y FM (1/cm2/s)
703 X-Y FE (1/cm2/s)
704 X-Y FN (1/cm2/s)
705 Y-Z DE (mSv/hr)
706 Y-Z FM (1/cm2/s)
707 X-Z DE (mSv/hr)
708 X-Z FM (1/cm2/s)
411 [F]?n!(1/cm^2!/1ppp) vs X-Y (c
412 [F]?ch.h!(1/cm^2!/1ppp) vs X-Y
Ok
Close
BH_max(T) 0.
BV_max(T) 0.
B_max(T) 0.
NBx 20
NBy 20
NBz 20
Xmin/cm -2200.0
Ymin/cm -727.4094
Zmin/cm -1.66e+0
Xmax/cm 2200.0
Ymax/cm 647.2246
Zmax/cm -639.945
Y-Z
X-Z
X-Y
X= 0.
Y= 0.
Z= 0.
3D plane x-section
3D-Visualization
WireFrame
1:1 scale
OFF
Magnetic field
OFF
Load Track 1 1 OFF
Materials
Particles
Run 1 Add
H: 0 V: 0 ShiftH 0.0 ShiftV 0.0
Load Hist -2 6 ON(706)
Hist Norm 1
View Format
Reset
<<
>>
Draw
Print
Grab
Quit
0
-300
-600
cm
-1.65e+05
-1.10e+05
-5.50e+04
ILC 1.5-km BDS
1.3e+05
0.0e+00
10^6 10^5 10^4 10^3 10^2 10^1 10^0 10^-1 10^-2
Y
Z
Aspect Ratio: Y:Z = 1:120.575

MARS15

A setup can be made of up to 100 composite materials, with arbitrary 3-D magnetic and electric fields. Powerful user-friendly GUI is used for visualization of geometry, materials, fields, particle trajectories and results of calculations.

It has 6 geometry options, flexible histograming, can use as an input MAD optics files through a powerful MAD-MARS Beam Line Builder, various tagging, biasing and other variance reduction techniques.

It can be interfaced to MCNP, ANSYS (thermal and stress), MESA/SPHINX (hydrodynamics), FRONTIER (magneto-hydrodynamics), DPMJET, GuineaPig, STRUCT, Geant4, ILCroot and other codes.

Current Developers

Many people participated in the MARS code development over its 37-year history

<u>Contributors to the current version MARS15(2010) are:</u>

N.V. Mokhov, P. Aarnio, Y.I. Eidelman, K.K. Gudima, M.A. Kostin, S.G. Mashnik, I.L. Rakhno, S.I. Striganov and I.S. Tropin

Plus invaluable feedback from R. Coleman, J. Dooling, H. Matsumura, L. Nicolas, G. Prior, V. Pronskikh, D. Reitzner and other 300 MARS users worldwide

TRANSPORTED PARTICLES AND ENERGIES

All important elementary particles with their corresponding decay modes are transported in the code. Arbitrary heavy ions with atomic mass A and charge Z are fully treated by MARS15. Their ID are coded as $ID = 1000Z + A - Z$.

Nucleons & Mesons	Gauge & Leptons	Hyperons
$p\ \overline{p}$	γ	$\Lambda\ \overline{\Lambda}$
$n\ \overline{n}$	$e^+\ e^-$	$\Sigma^+\ \overline{\Sigma}^+$
$\pi^+\ \pi^-\ \pi^0$	$\mu^+\ \mu^-$	$\Sigma^0\ \overline{\Sigma}^0$
$K^+\ K^-$	$\nu_e\ \overline{\nu}_e$	$\Sigma^-\ \overline{\Sigma}^-$
$K^0\ \overline{K}^0$	$\nu_\mu\ \overline{\nu}_\mu$	$\Xi^0\ \overline{\Xi}^0$
$K_L^0\ K_S^0$		$\Xi^-\ \overline{\Xi}^-$
		$\Omega^-\ \overline{\Omega}^-$

Maximum energy: 100 TeV. Minimal energies: 0.001 eV neutrons, 100 keV (currently) electrons and photons, and 1 keV hadrons, muons and heavy ions.

MARS15 EXCLUSIVE EVENT GENERATORS

Improved Cascade-Exciton Model code, **CEM03.03**, combined with the Fermi break-up model, the coalescence model, and an improved version of the Generalized Evaporation-fission Model (GEM2) is used as a default for hadron-nucleus interactions below 5 GeV. Recent multi-fragmentation extension.

The Los Alamos Quark-Gluon String Model code, **LAQGSM03.03 (2011)**, is used in MARS15 for photon, particle and heavy-ion projectiles at a few MeV/A to 1 TeV/A. This provides a power of full theoretically consistent modeling of exclusive and inclusive distributions of secondary particles, spallation, fission, and fragmentation products.

S. G. Mashnik, K. K. Gudima, A. J. Sierk, M. I. Baznat, N. V. Mokhov, "CEM03.03 and LAQGSM03.03 Event Generators for the MCNP6, MCNPX and MARS15 Transport Codes", LANL LA-UR-08-2931 (2008).

For quite some time, MARS has used the Dual-Parton Model code, **DPMJET3**,for the very first vertex in a cascade tree. This is used in our numerous studies for the LHC 7x7 TeV collider and its detectors, and at very high energies up to 100 TeV.

MARS15: Exclusive, Inclusive & Hybrid

Most of processes in MARS15, such as electromagnetic showers, hadron-nucleus interactions, decays of unstable particles, emission of synchrotron photons, photohadron production and muon pair production, can be treated exclusively (analogously), inclusively (with corresponding statistical weights), or in a mixed mode. The choice of method is left for the user to decide, via the input settings.

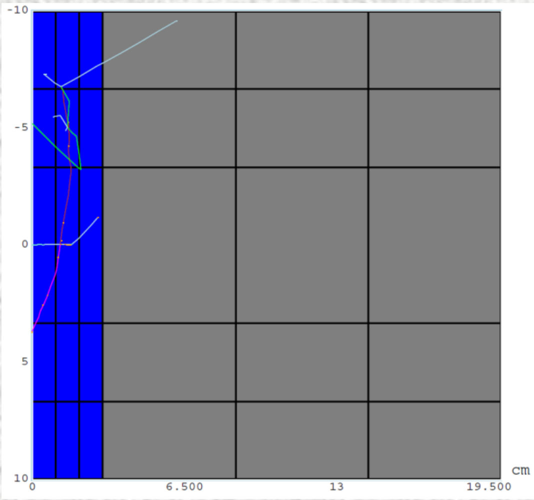
Other variance reduction techniques used in MARS: weight-window, splitting and Russian roulette, exponential transformation, probability scoring, step/energy cutoffs.

Goal: Maximize computing efficiency $\varepsilon = t_0/t$, where t is CPU time needed to get a RMS error σ equal to the one in the reference method with CPU time t_0 provided σ < 20%.

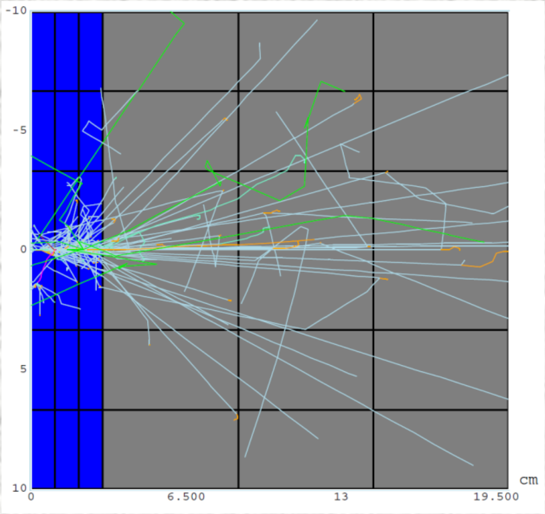
Example: EMS

One 10-GeV e^+ on 3cm W + 17cm concrete

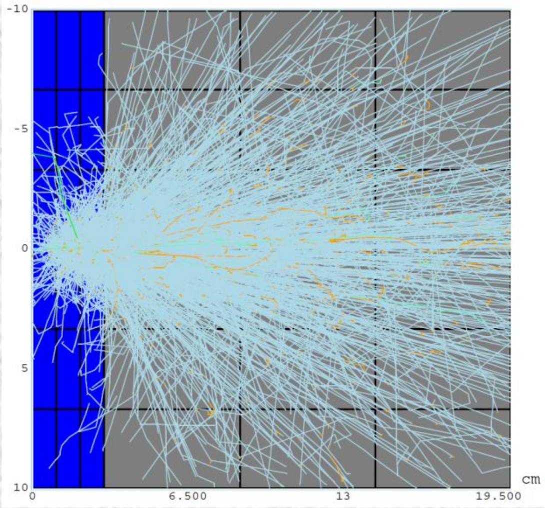
Inclusive



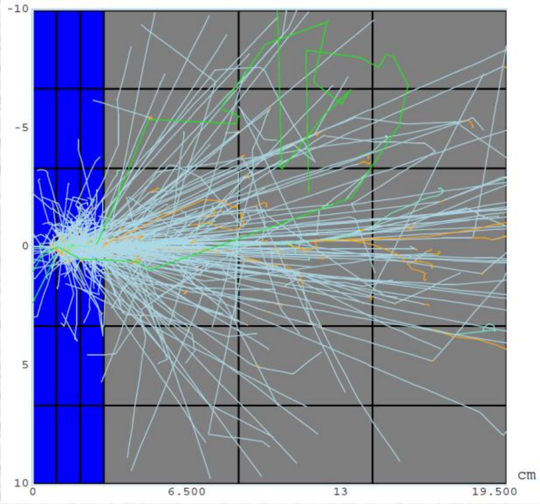
Hybrid-10



Exclusive



Hybrid-20



PHYSICS PROCESS BIAS CONTROL (1)

A user-friendly global bias control in several important processes via a card **BIAS** with variables which define parameters of forced (inclusive) and analog (exclusive) sampling. Eight parameters/processes (-1 for analog, 0.001 to 1 forced with Russian Roulette, 0 to suppress):

- **PPIKDEC** - decays of unstable ptcls & nuclei. Default: -1.
- **PMUPRMT** - prompt muon production . Default: 0.05
- **PMUBEHE** – Bethe-Heitler muon production. Default: 0.03
- **PMUGVM** – γA vector mesons muons. Default: 0.02
- **PMUANN** – $e^+e^- \rightarrow \mu^+\mu^-$ annihillation. Default: 0.03
- **PPHNUC** – photo-nuclear reactions. Default: 0.02
- **PELNUC** – electro-nuclear reactions. Default: 0.05
- **PPBAR** - anti-proton production. Default: 0.05

PHYSICS PROCESS BIAS CONTROL (2)

- **KEMINCL**, 8th parameter of PHOT card: electromagnetic shower modeling control with 0 for fully inclusive; -1 for fully exclusive (five EMS bias keys of BIAS card are automattically converted to -1); N > 0 for hybrid (exclusive for first N generations and inclusive after that).

- **IQGSM**, 4th parameter of ICEM card: nuclear inelastic vertex control with 0 for inclusive, 1 for exclusive with appropriate mixture of CEM and LAQGSM event generators, 2 for pure LAQGGSM exclusive modeling.

- Processes for stopping and very low-energy particles: majority is now modeled exclusively (can be switched to inclusive internally).

Process ID in Subroutine MFILL

SUBROUTINE MFILL (IHTYP,NREG,IM,JJ,E1,E2,DELE,W,X1,Y1,Z1,X2,Y2,Z2,DCX,DCY,DCZ,STEP,TOF,NI,IDPRC)

C 1 DPA ELASTIC AND INELASTIC
C 2 RECOIL NUCLEUS LOCAL DEPOSITION (NON-LAQGSM)
C 3 Local deposition of heavy ions at AA-vertex (NON-LAQGSM)
C 4 STAR DENSITY
C 5 FISSION CEM LOCAL (NON-LAQGSM)
C 6 FISSION >5 GEV LOCAL (NON-LAQGSM)
C 7 HEAVY FRAGMENTS LOCAL DEPOSITION (NON-LAQGSM)
C 8 d, t, He3 and He4 LOCAL DEPOSITION (NON-LAQGSM)
C 9 SURFACE CROSSING BY HADRONS AT IND(6)=T
C 10 STAR DENSITY AT IND(6)=T
C 11 FLUENCE AT IND(6)=T
C 12 ENERGY DEPOSITION by SUB-THRESHOLD hadrons
C 13 SURFACE CROSSING BY NEAR-THRESHOLD HADRONS
C 14 FLUENCE BY NEAR-THRESHOLD HADRONS
C 15 ENERGY DEPOSITION ON STEP BY NEAR-THRESHOLD HADRONS
C 16 SURFACE CROSSING BY NEUTRAL HADRONS OR IN VACUUM
C 17 SURFACE CROSSING BY CHARGED HADRONS IN MATERIAL
C 18 ENERGY DEPOSITION ON STEP BY CHARGED HADRONS
C 19 FLUENCE BY HADRONS
C 20 ENERGY DEPOSITION BY SUB-THRESHOLD e+e- from hadrons
C 21 e+e- vertex by muon
C 22 FLUENCE BY MUONS
C 23 SURFACE CROSSING BY MUONS
C 24 ENERGY DEPOSITION ON STEP BY MUONS
C 25 BREMS VERTEX BY MUONS
C 26 NUCL VERTEX BY MUONS
C 27 ENERGY DEP BY SUB-THRESH BREMS OR NUCL PRODUCTS OF MUONS
C 28 ENERGY DEPOSITION BY SUB-THRESHOLD MUONS
C 29 ENERGY DEPOSITION BY HEAVY FRAGMENTS FROM MUON CAPTURE
C 30 MUON DECAY VERTEX
C 31 SURFACE CROSSING BY EMS
C 32 EMS FLUENCE IN VACUUM OR PHOTON FLUENCE
C 33 e+e- FLUENCE AND ENERGY DEPOSITION ON STEP
C 34 ENERGY DEPOSITION BY SUB-THRESHOLD EMS
C 35 DELTA-ELECTRON VERTEX
C 36 LE neutron vertex
C 37 LE NEUTRON FLUENCE ON STEP
C 38 LE NEUTRON SURFACE X-ING
C 39 LE NEUTRON SURFACE CROSSING AT IND(6)=T
C 40 LE NEUTRON FLUENCE AT IND(6)=T
C 41 LE NEUTRON LOCAL ED: no new n or gamma generated
C 42 LE NEUTRON LOCAL ED: recoil proton below 50 keV (E1=Ep)
C 43 LE NEUTRON: n+p -> d+gamma reaction
C 44 LE NEUTRON LOCAL ED: vertex non-fission MCNP (E1=Eterm)
C 45 LE NEUTRON LOCAL ED: capture on Li or B in non-LAQGSM (E1=Ehi)
C 46 LE NEUTRON LOCAL ED: sub-threshold (E1=En)
C 47 LE NEUTRON LOCAL ED: SUB-THRESHOLD AT IND(6)=T
C 48 LE NEUTRON LOCAL ED: fission
C 49 LE NEUTRON LOCAL ED: vertex non-fission BNAB
C 50 FLUENCE BY NEUTRINO
C 51 GAS CAPTURE (HE)
C 52 GAS CAPTURE (LE)

MARS15: Tagging

- Enhanced tagging module in MARS15 allows one to tag the origin of a given signal/tally: geometry, process and phase-space. Invaluable in studying a source term and for sensitivity analysis.

- User-friendly access to process ID at scoring (histograming) stage: flags to 52 process types.

Tagging in Subroutine MFILL (1)

```
*    KORIG = 0 - primary beam
*            1 - muons,   unstable particle decay
*            2 - muons,   prompt at hA-vertex
*            3 - muons,   Bethe-Heitler pair
*            4 - muons,   e+e- annihilation
*            5 - hadrons, hA-vertex
*            6 - hadrons, elastic
*            7 - hadrons, from muons
*            8 - hadrons, unstable particle decay
*            9 - hadrons, EMS
*           10 - hadrons, recoil LEN
*           11 - hadrons, from neutrinos
*           12 - EMS,     induced by photons from pi0-decay
*           13 - EMS,     induced by synchrotron photons
*           14 - EMS,     induced by g,e+,e-, at hA vertex
*           15 - EMS,     induced by knock-on electrons from muons or hadrons
*           16 - EMS,     induced by g,e+,e- from unstable particle decay
*           17 - EMS,     induced by prompt e+e- from muons or hadrons
*           18 - EMS,     induced by brems photons from muon
*           19 - EMS,     induced by photons from stopped muons
*           20 - EMS,     induced by photons from low-energy neutrons
*           21 - muons,   vector mesons
```

Tagging in Subroutine MFILL (2)

```
Cc Example-1: Tagging-1
C      if(ihtyp.ne.3) return
C
C      de=w*(e1-e2)
C      if(de.le.0.0d0) return
C      kkmsk=0
C* D21
C      if(nreg.ge.1608.and.nreg.le.1644) then
C        m=1
C        if(nrorig.eq.1603.or.nrorig.eq.1652) then
C          kkmsk=1              ! up/dw mask as origin
C        end if
C*     fill corresponding arrays
C      .........................
C      end if
C
Cc Example-2: Tagging-2
C
C      if(nreg.eq.9) then
C        write(71,100)NI,NREG,IM,JJ,W,E1,E2,STEP,
C     &      XORIG,YORIG,ZORIG,WORIG,EORIG,IORIG,KORIG,NRORIG,IMORIG
C 100    format(' NI,NREG,IM,JJ,W,E1,E2,STEP = ',i7,I5,2i3,4(1pe11.4)/
C     &      ' XORIG,YORIG,ZORIG,WORIG,EORIG,IORIG,KORIG,NRORIG,IMORIG'
C     &      ,'= ',5(1pe11.4),2i3,2i5)
C      end if
```

Tagging in Subroutine MFILL (3)

```
*c Example-3: fill in histograms declared in MHSETU
*
*    REMEMBER, HBOOK IS A SINGLE PRECISION ENGINE
*    DON'T FORGET CONVERSIONS OF THE FOLLOWING TYPE:
*
*     REAL EEH,WWH,XL,YL,WH
*     EEH=REAL(E1)
*     WWH=REAL(W)
*     CALL HFILL(ID,EEH,0.,WWH)
*     ...
*     CALL HF2(ID,XL,YL,WWH)
*
*
*c Example-4: Write particles crossed the boundary between regions 2 and 3
*     if(ihtyp.eq.2.and.nreg.eq.2.and.nreg2.eq.3) then
*       write(71,100)ni,JJ,E2,W,X2,Y2,Z2,DCX,DCY,DCZ,step
* 100     format(2i7,9(1pe13.5))
*     end if
*
*c Example-5: Write particles crossed a specified boundary
*     if(ihtyp.eq.2.and.abs(x-5.d0).lt.10.d0) then
*       if(z1.lt.25.d0.and.z2.gt.25.d0) then
*         write(71,100)ni,JJ,E2,W,X2,Y2,Z2,DCX,DCY,DCZ,step
* 100       format(2i7,9(1pe13.5))
*       end if
*     end if
```

Tagging in Subroutine MFILL (4)

```
*c Example-6: collect the recoil energy spectrum produced by nuclear elastic
*c          collisions of a particle JJ on ZCNUCL > 1
*     if(idprc.eq.1.and.zcnucl.gt.1.0d0) then
*       if(zresid.eq.zcnucl.and.aresid.eq.acnucl) then
*c          add W*E1 to a corresponding array/histogram ! note here: E1=TRESID
*       end if
*     end if
*
```

Subroutine EVENTIN

EVENTIN (NI,IO,WO,EO,AC,ZC,ILAQGSM,ICEM)

Full access to stack EWX of secondaries in every inelastic nuclear interaction in history NI for projectile IO with weight WO and kinetic energy EO on nucleus with mass=AC and charge=ZC for model parameters ILAQGSM and ICEM

ENDF/MCNP x-sections in MARS15

The ENDF/MCNP **physics (not geometry!)** mode - instead of the default BNAB one - is strongly recommended in MARS15 for the precise description of neutron interactions **at neutron energies below 14.5 MeV** in cases when they are important.

It provides:

- Exact treatment of neutron interactions with arbitrary material (contrary to a limited material list available in BNAB).
- Secondaries generated in MCNP modules in collisions, fission and thermal neutron capture – photons, protons, deuterons and heavier fragments – are directed back to the MARS modules for a corresponding treatment.

The price one pays is an increase of CPU time per history, substantial, e.g., when thermal neutrons drive the problem.

ENDF/MCNP Option at E < 14.5 MeV

To use this option, a user must have any of the MCNP family code with corresponding libraries obtained from the RSICC center in the USA or NEA Databank in Europe and Japan and installed on his/her group computer.

All the files for MCNP-to-MARS bootstraping can be downloaded from the MARS web page. A link of MARS materials to the MCNP code is done in the MARS.INP file according to the MCNP material format.

MARS15+DeTra for Nuclide & Activity Calculations

Control via new variable IDTR, 5th on CTRL card:

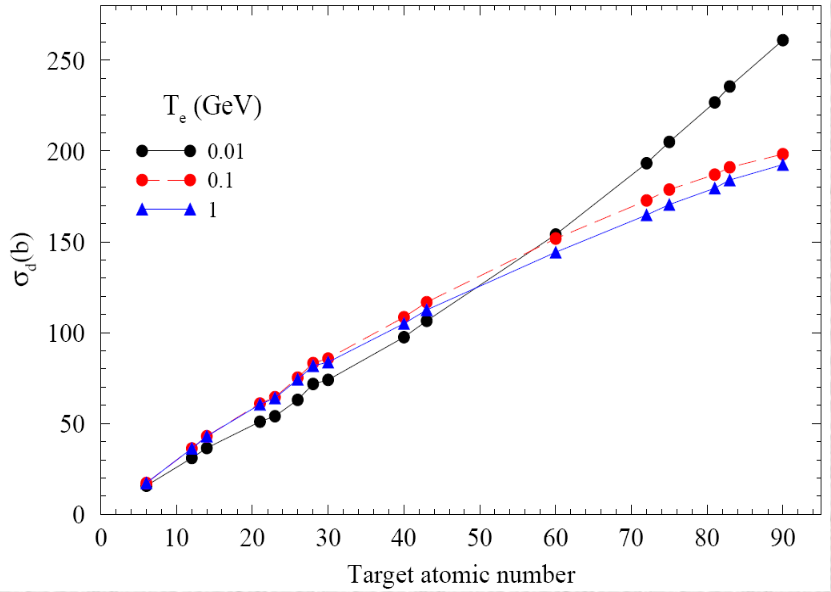
1. **IDTR=0** (default): Standard MARS15 run, nuclide production rates in materials specified by NCLD and IMNC cards of MARS.INP with interface files NUCLIDES generated.
2. **IDTR=1**: Built-in DeTra is called to solve the Bateman equations governing the decay and transmutation of nuclides using transmutation trajectory analysis.
3. **IDTR=3**: The output files of step 2 are processed by running MARS executable again.

See Vitaly's presentation for details/example

DPA Model in MARS15 (1)

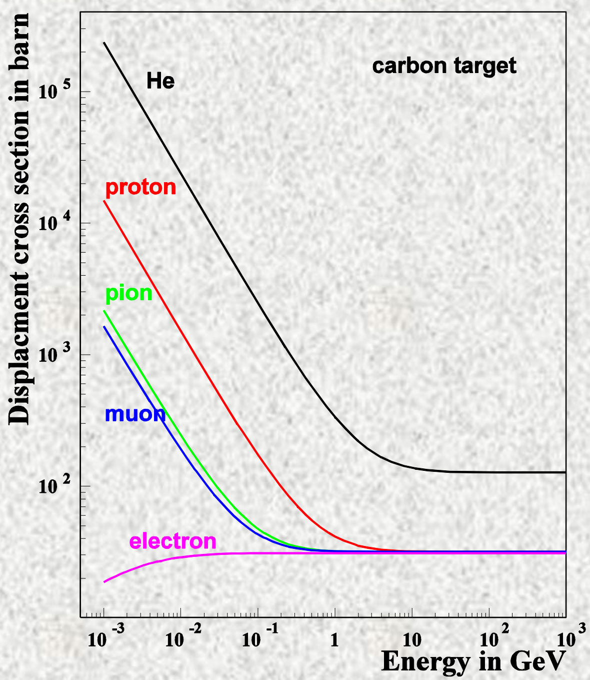
In a course of simulation of particle interactions and transport, MARS15 keeps track of all processes which can cause displacement of atoms (DPA) from their equilibrium position that results in radiation damage. The value of DPA for elastic and inelastic nuclear interactions is calculated within the Lindhard-Robinson model above the displacement energy Td, the minimal transferred kinetic energy required to produce a displaced atom (Td ~25-90 eV).

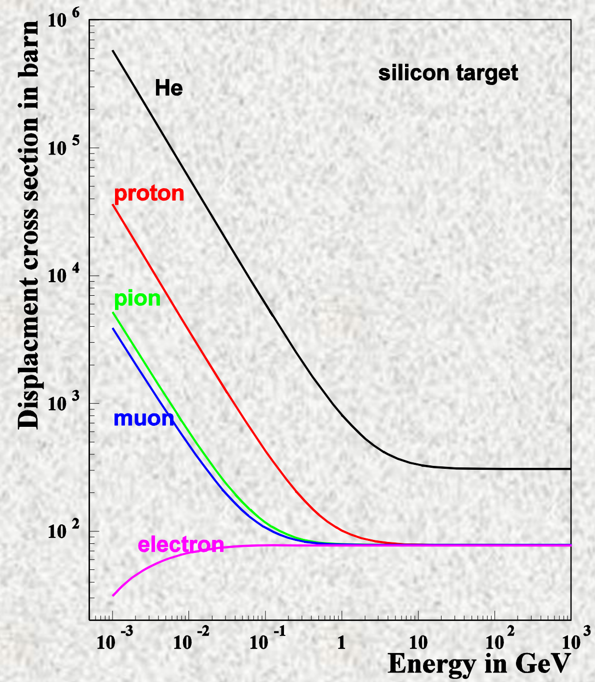
Using damage x-section sd, primary knock-on atom (PKA) x-section sPKA, damage function, elastic scattering x-section and nuclear form-factor, one calculates corresponding DPA for arbitrary projectile.



DPA Model in MARS15 (2)

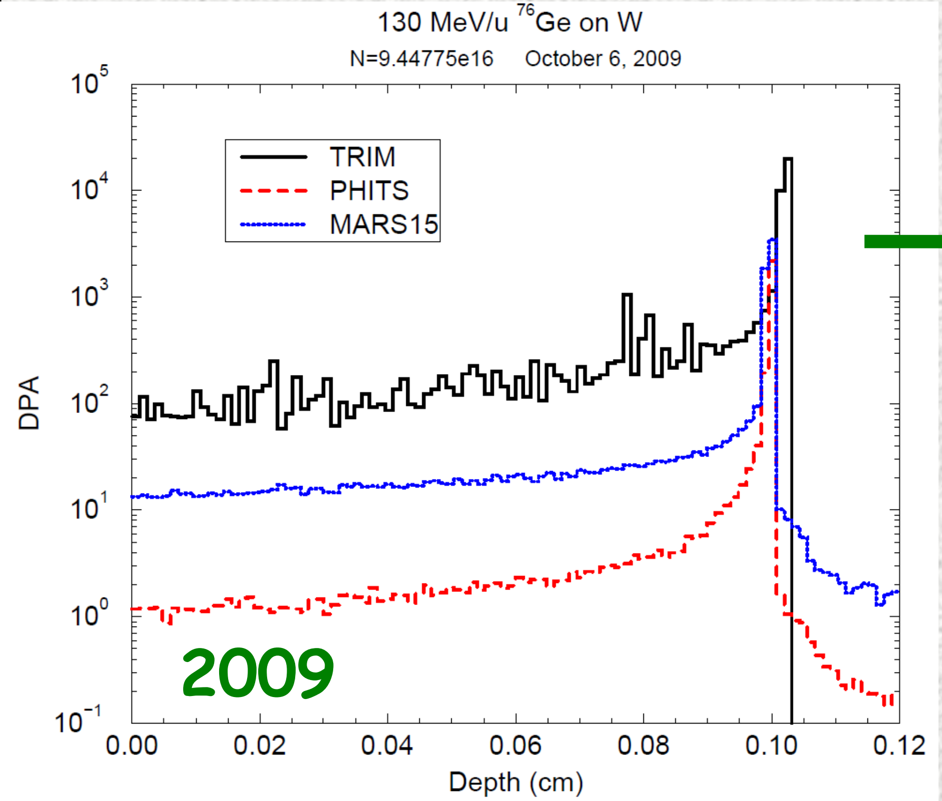
Displacement cross section due to Coulomb scatternig

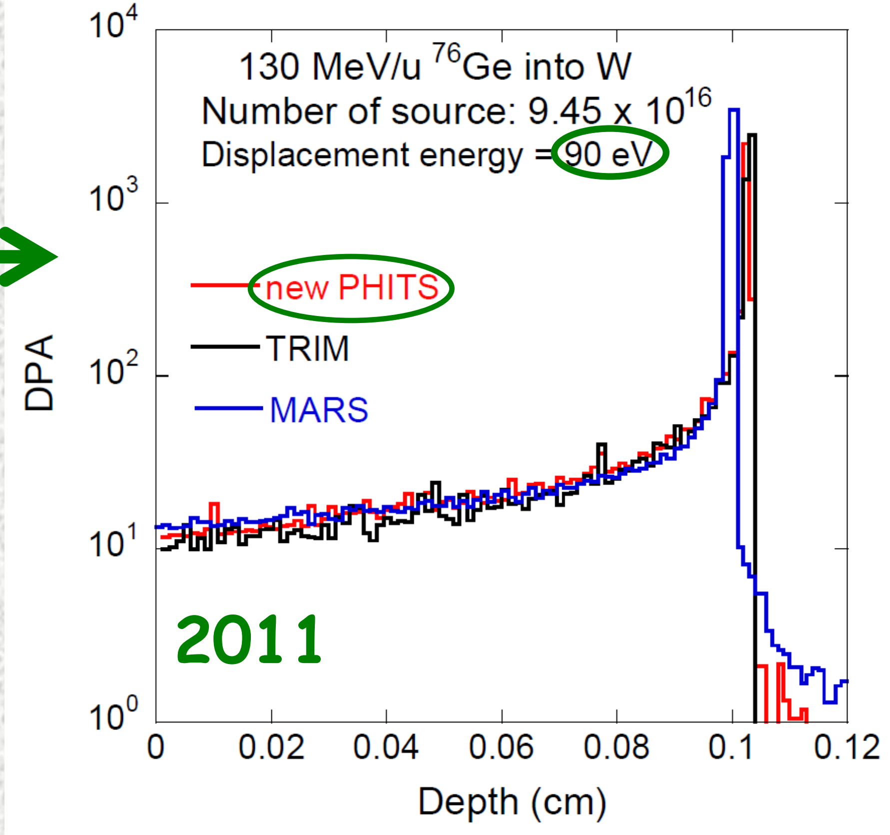




All products of elastic and inelastic nuclear interactions as well as Coulomb elastic scattering (NIEL) of transported charged particles (hadrons, electrons, muons and heavy ions) from 1 keV to 10 TeV contribute to DPA in MARS15 model.

DPA Comparison: 130 MeV/u ^{76}Ge on W





Pencil beam, uniform in R=0.03568 cm disc.
Target W_{nat}, cylinder with R=0.03568 cm, L=0.12 cm

TRIM and PHITS results: Courtesy Yosuke Iwamoto

GEOMETRY DESCRIPTIONS IN MARS15 (1)

Six geometry description options

1. **Standard**: heterogeneous *R-Z-Φ* cylinder (in most cases this is just a mother volume).

2. **Non-standard**: arbitrary user-defined in Fortran or C.

3. **Extended**: a set of contiguous or overlapping geometrical shapes, currently, boxes, spheres, cylinders, truncated cones, tetrahedra, elliptical tubes, elliptical cone and conical sector. Can be subdivided into many sub-regions in each direction; arbitrary transformation matrices can be applied to any object.

GEOMETRY DESCRIPTIONS IN MARS15 (2)

4. **MCNP**: read in an input geometry description in the MCNP format.

5. **FLUKA**: read in an input geometry description in the FLUKA format (requires pre-processing).

6. **ROOT**: ROOT solid body geometry C++ description and tracking, directly usable with already-existing GEANT4 models; powerful 3-D visualization capabilities; beta-test stage. (See Igor Tropin's presentation for details/examples).

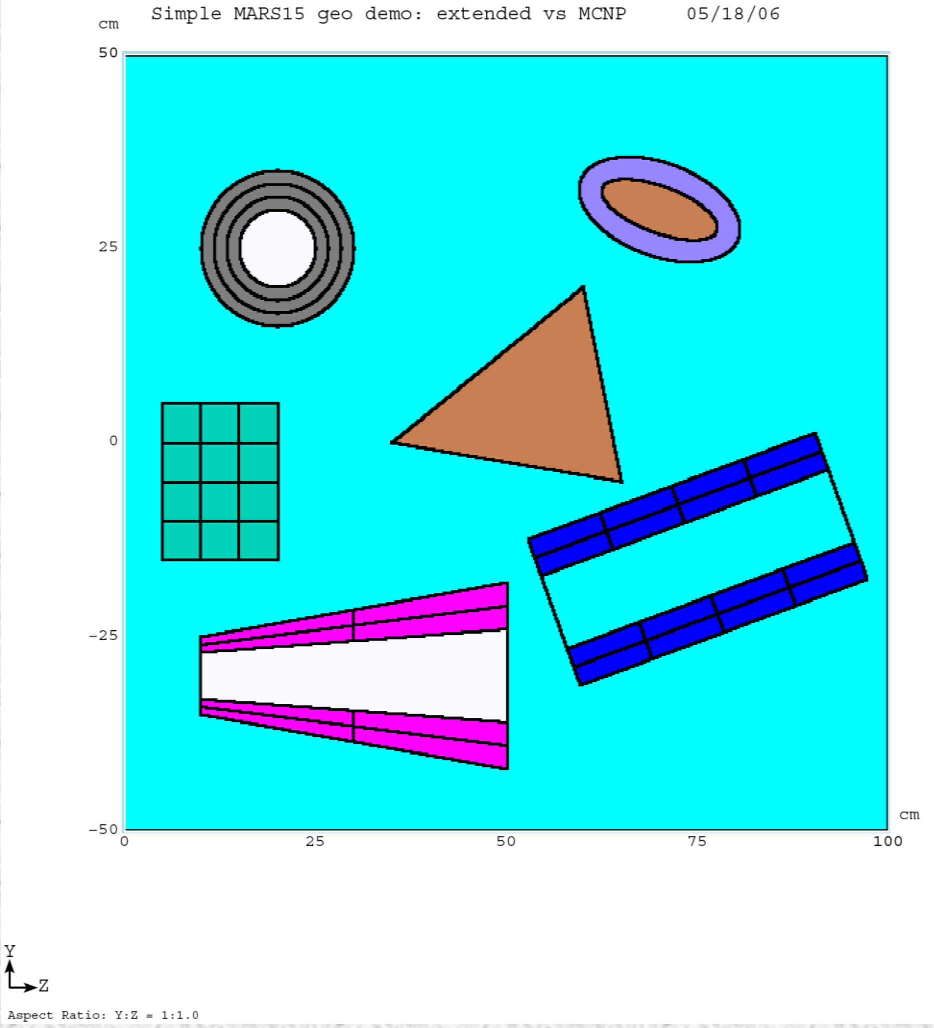
Extended Geometry

Extended Geometry zones are constructed from a set of contiguous or overlapping geometrical shapes, which currently consists of **Box, Cylinder, Sphere, Cone, Tetrahedron, Elliptical Tube, (Toroid), Elliptical Cone, Conical Sector.** There can be up to 10^5 Extended Geometry shapes declared, where each declared shape is counted as a MARS zone. A single shape can be sub-divided into sub-zones, with each sub-zone counting towards the maximum limit.

Zone overlapping in the extended geometry mode means in particular that in this mode a user doesn't need to care about zone numbering when one large zone is filled with small objects. The specifications for the geometric shapes are controlled by lines in the input file GEOM.INP.

SIMPLE GEO EXAMPLE: GEOM.INP

```
 Extended Demo  05/17/06
OPT
box-1      1 0 2   0.  -5.   5.  10.  10. 15. 1 4 3
cyl-1a    -2 1 7   0.   0.   0.   0.   5. 20.
cyl-1a    -2 1 1   0.   0.   0.   5.  10. 20. 4 2
ball-a     3 0 8   0.   25. 20.   0.   5.
ball-b     3 0 3   0.   25. 20.   5.  10. 3
cone-in   -4 0 0   0. -30.  30.   0.   3.  0.  6. 20.
cone-out  -4 0 4   0. -30.  30.   3.   5.  6. 12. 20. 2 2
th         5 0 6   0. 0. 35. 5. 3. 55. 0. 20. 60. 0. -5. 65.
ell-tub1  -6 2 6   0.   0.   0.   8.   3.  0.  40.
ell-tub2  -6 2 5   0.   0.   0.   8.   3.  3.  40.
TR1  0.  -15. 75. -20.
TR2  0.   30. 70.  20. 90.
stop
```



SAME EXAMPLE: MARS.INP with MCNP Geometry

```
 Extended & MCNP Demo  05/17/06
/home/mokhov/restricted/mars15/dat
INDX 3=F 5=T 16=T
CTRL 1
NEVT 50
ENRG 10.
ZSEC 100.
RSEC 50. 101=7
NMAT 7
MATR 'NBS2' 'SCI' 'CONC' 'MRBL' 'CAST' 'S316' 'AIR'
NHBK 1
STOP
*MCNP START
1  7  -0.00129     2 -1  (-26:27:25)   8 17 (-19:21:23) imp:n,p=1
2  2  -0.7903      -2     -3   -6          imp:n,p=1
3  2  -0.7903      -2    3 -4   -6          imp:n,p=1
4  2  -0.7903      -2    4 -5   -6          imp:n,p=1
5  2  -0.7903      -2    5      -6          imp:n,p=1
6  2  -0.7903      -2     -3  6 -7          imp:n,p=1
7  2  -0.7903      -2    3 -4  6 -7          imp:n,p=1
8  2  -0.7903      -2    4 -5  6 -7          imp:n,p=1
9  2  -0.7903      -2    5    6 -7          imp:n,p=1
10  2  -0.7903      -2     -3  7          imp:n,p=1
11  2  -0.7903      -2    3 -4  7          imp:n,p=1
12  2  -0.7903      -2    4 -5  7          imp:n,p=1
13  2  -0.7903      -2    5     7          imp:n,p=1
14  7  -0.00129     -8    -9               imp:n,p=1
15  1  -7.0        -8  9 -10    -11         imp:n,p=1
16  1  -7.0        -8  9 -10   11 -12       imp:n,p=1
17  1  -7.0        -8  9 -10   12 -13       imp:n,p=1
18  1  -7.0        -8  9 -10   13           imp:n,p=1
19  1  -7.0        -8 10       -11          imp:n,p=1
20  1  -7.0        -8 10     11 -12         imp:n,p=1
21  1  -7.0        -8 10     12 -13         imp:n,p=1
22  1  -7.0        -8 10     13             imp:n,p=1
23  0             -14                      imp:n,p=1
24  3  -2.35      14 -15                   imp:n,p=1
25  3  -2.35      15 -16                   imp:n,p=1
26  3  -2.35      16 -17                   imp:n,p=1
27  0             -18  19 -21              imp:n,p=1
28  4  -2.7      18 -22   19 -20           imp:n,p=1
29  4  -2.7      18 -22   20 -21           imp:n,p=1
30  4  -2.7      22 -23   19 -20           imp:n,p=1
31  4  -2.7      22 -23   20 -21           imp:n,p=1
32  6  -7.92         -24   26 -27          imp:n,p=1
33  5  -7.31      24 -25   26 -27          imp:n,p=1
34  0          1                           imp:n,p=0
1     rcc     0 0 0     0 0 100     50
2     rpp    -10 10    -15 5     5 20
3     py   -10
4     py    -5
5     py     0
6     pz    10
7     pz    15
8  1  rcc     0 0 -20    0 0 40    10
9  1  cz     5
10 1  cz     7.5
11 1  pz   -10
12 1  pz     0
13 1  pz    10
14    s      0 25 20    5
15    s      0 25 20    6.667
16    s      0 25 20    8.333
17    s      0 25 20   10
18    k/z   0 -30 -30   .005625
19    pz     10
20    pz     30
21    pz     50
22    k/z   0 -30 -22      .015625
23    k/z   0 -30 -18.57   .030626
24 2 sq    0  64  9    0 0 0   -576   0 0 0
25 2 sq    0 121 36    0 0 0 -4356   0 0 0
26    px  -40
27    px   40
mode n p

m1   2004 -.02    29000 -.38    13027 -.2      41093 -.280522      50000 -.119478   $   NBS2
m2   1001 -.13314  6000 -.86651  7014 -.00016   8016 -.00019            $   SCI
m3   1001 -.006    6000 -.030    8016 -.500     11023 -.010 13027 -0.03 &   $   Conc
   14000 -.200   19000 -.010   20000 -.200    26000.42c -.014
m4  20000 -.400431 6000 -.120005 8016 -.479564                  $   MRBL
m5   6000 -.0365  14000 -.025   25055 -.0018   26000.42c -.9347  29000 -.002 $ CAST
m6  24000 -.17    25055 -.02    26000.42c -.655 28000  -.12  14000 -.01    42000 -.025 $ S316
m7   7014  .78443  8016  .21076 18000.42c 4.671E-3 6000 1.39E-4 gas=1      $   Air
vol  1 33r
*MCNP END
```

Geometry Type Mixing and Volumes

All six geometry types can co-exist in a setup description.

Hierarchy: EMF (extended, MCNP or FLUKA) can overwrite all or part of S (standard); NS&R (non-standard & ROOT) can overwrite all or part of S and EMF. Arbitrary number of regions (currently up to 10^5).

Volumes of all regions are auto-calculated for the predefined shapes.

In case of geometry type mixture or/and overlapping regions, one uses a short Monte-Carlo session of the code to calculate the volumes (activated by IVOL of the CTRL card and optional RZVL card).

A corresponding output file VOLMC.NON provides calculated volumes with statistical errors, and is directly linked to the main code:

```
VOLUME(     2) =   0.7970742E+05   ! +/-   0.08%,  M=      1   Q1-hech1
VOLUME(     3) =   0.7957665E+05   ! +/-   0.08%,  M=      2   Q1-hech2
VOLUME(     6) =   0.1834548E+05   ! +/-   0.16%,  M=      5   Q1-ep13
```

MATERIALS

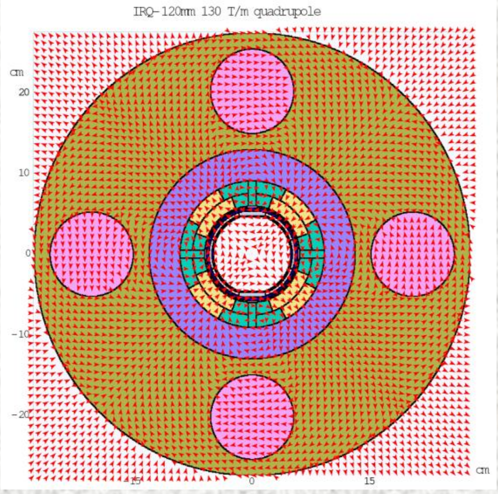
A list of built-in materials includes 165 entries. Many kinds of steel, concrete, magnet coils, superconducting and permanent magnet materials, insulators, as well as cast iron, mineral oil, gadalinium-loaded scintillator, etc. Separate treatment of gaseous and liquid states. The default densities can be re-defined by the MTDN card.

User-defined composite material option on top of that is kept (sbr. MIXTUR).

MAGNETIC FIELDS

To describe the magnetic field components BX,BY,BZ in a region N, the user puts IND(4)=T in MARS.INP and provides a subroutine FIELD. The same routine is used to describe an electrical field. One can use a corresponding OPERA-calculated map or analytical expressions to find the field components in the point (X,Y,Z) or region N. The unit for magnetic field is Tesla.

In most cases Z-coordinate or region number(s) are used to identify a magnetic element (dipole, quadrupole, solenoid, etc.) to use a corresponding map associated with this element. A 2-D or 3-D field map is read in a user routine SUFI at the initialization stage and transferred to an interpolation algorithm of FIELD.



Always use GUI to check polarities!

GRAPHICAL-USER INTERFACE

It displays all the details of the encoded geometry at arbitrary cross-sections at a desired zoom in/out level, showing region numbers, color-coded materials and magnetic fields, color-coded particle tracks, and calculated 2D histograms. Invaluable in building and debugging the model and studying its property and performance.

Tcl/Tk based 2D MARS-GUI-SLICE - a powerful user-friendly tool linked to the executable – **has undergone substantial improvements in 2011.** One of the impressive examples is switching between "Global" and "Beamline" coordinate systems with appropriate presentation of materials, particle tracks and histograms.

MARS Input Files

MARS.INP: **mandatory** file to define the main operating parameters for running the simulation: mother volume, materials, beam energy, energy cutoffs, bias parameters, number of histories to run, RZ histograms, etc. There are many switches and selections that can be set. The number and size of the Standard Zones are defined here. The file can also contain an optional section for importing MCNP or FLUKA geometry.

GEOM.INP: extended geometry description (optional).

XYZHIS.INP: XYZ-histogram description (optional).

Problem-dependent optional files: MAD optics, pre-generated sources (DPM.EVE, BLOSS, multi-step files, etc.), magnetic field maps (D1.MAP, Q5.MAP, etc.).

XSDIR: to interface to ENDF x-section database.

MARS Output Files

MARS.OUT: **main** output file which contains startup initialization information, and numerous numerical distributions and integrals calculated in the MC session.

MTUPLE, MTUPLE.NON, MTUPLE.EXG, MTUPLE.MCNP: most important results re-formatted in a convenient tabular form for the geometry option used in the run.

mars.hbook: HBOOK 1D and 2D histograms requested to be filled in the run (RZ volume and surface, XYZ, user's).

Problem-dependent optional files: leakage, surface crossing, multi-step files, NUCLIDES for DeTra, etc.

DUMP: intermediate dump.

VOLMC.NON: Monte-Carlo calculated volumes.

I/O file names are defined and can be redefined in marsmain.f

MARS15 Tallies

Tallies in these files include volume and surface distributions (1D to 3D) of particle flux, energy, reaction rate, energy deposition, residual nuclide inventory, prompt and residual dose equivalent, DPA, gas production and capture rates, event logs, intermediate source terms, etc.

Most of the tallies can be viewed within the MARS GUI on top of a corresponding geometry slice.

Once in the event generator mode, double-differential cross sections, momentum distributions, multiplicities and alike are collected in the output files.

HISTOGRAMING

In addition to RZ volume and surface histograming, user-friendly flexible XYZ-histograming option is available. It allows scoring numerous distributions – total and partial particle fluxes, star density, energy deposition, DPA, gas generation and capture, prompt and residual dose rates, particle spectra etc – in boxes arbitrary positioned in a 3D system, independent of geometry description.

XYZ-Histograming: XYZHIS.INP

```
XYZ histo test with histo list  28-Apr-2011

xyz -20. 20. -0.4 0.4 0. 50. 40 1 50 XZ-scan_at_|y|<0.4
STA DRE FLT FLP FLN FLN>0.02 FLK FLM>0.1 FLG FLE DAB DPA
DET DET>0.02 DEP DEN DEK DEM DEG DEE
PDT PDP PDN PDK PDM PDG PDE

xyz -0.4 0.4  -10. 10.  0. 50. 1 20 50 YZ-scan_at_|x|<0.4
PDT>0.1 DAB>0.1 DPA>0.1

xyz -5. 5.  -5. 5.  10. 12. 50 50 1 XY-scan_at_z=10-12cm
DRE DRE>0.1

xyz 0. 5. 2. 7. 10. 15. 1 1 1 Spectrum-1_in_a_5x5x5_cm_cube
SPP SPN SPK SPM SPG SPE

stop
```

Not only flux, but any value can be histogramed above a threshold defined, e.g., as DAB>0.05

XYZ-Histograming: Histogram List

```
! XYZ X1 X2 Y1 Y2 Z1 Z2 NX NY NZ TEXT
! Histo types (1-38):
C STA- star density                E>50 MeV (cm^-3 s^-1)
C DRE- 30d/1d residual dose on contact      (mSv/hr)
C FLT- total flux of hadrons        E>ETFT   (cm^-2 s^-1)
C FLP- flux of protons              E>ETFH   (cm^-2 s^-1)
C FLN- flux of neutrons             E>ETFN   (cm^-2 s^-1)
C FLK- flux of pions/kaons          E>ETFH   (cm^-2 s^-1)
C FLM- flux of muons                E>ETFM   (cm^-2 s^-1)
C FLG- flux of photons              E>ETFG   (cm^-2 s^-1)
C FLE- flux of e-e+                 E>ETFE   (cm^-2 s^-1)
C
C DAB- absorbed dose                          (Gy/yr)  at 2.e7
s/yr
C DPA- DPA                                  (DPA/yr) at 2.e7 s/yr
C DPH- DPA, NIEL hadrons and muons          (DPA/yr) at
2.e7 s/yr
C DPN- DPA, neutrons at E < 14 MeV          (DPA/yr) at
2.e7 s/yr
C DPE- DPA, EMS                             (DPA/yr) at 2.e7
s/yr
C HYD- Hydrogen gas capture                    (cm^-3 s^-1)
C HEL- Helium gas capture                    (cm^-3 s^-1)
C TRI- Tritium gas capture                   (cm^-3 s^-1)
C
C DET- FTD prompt dose equivalent, total     (mSv/hr)
C DEP- FTD prompt dose equivalent, proton    (mSv/hr)
C DEN- FTD prompt dose equivalent, neutron   (mSv/hr)
C DEK- FTD prompt dose equivalent, pi/K      (mSv/hr)
C DEM- FTD prompt dose equivalent, muon      (mSv/hr)
```

```
C DEG- FTD prompt dose equivalent, photon   (mSv/hr)
C DEE- FTD prompt dose equivalent, e+e-     (mSv/hr)
C
C PDT- power density, total                 (mW/g or Gy/s)
C PDP- power density, proton                (mW/g or Gy/s)
C PDN- power density, neutron               (mW/g or Gy/s)
C PDK- power density, pion/kaon             (mW/g or Gy/s)
C PDM- power density, muon                  (mW/g or Gy/s)
C PDG- power density, photon                (mW/g or Gy/s)
C PDE- power density, e-e+                  (mW/g or Gy/s)
C
C Don't use DLT: it is exremely slow now!!!
C DLT- instantaneous temperature rise       (degC or
degK) per AINT (ppp)
C
C Default cutoff energy is used for spectra:
C
C SPP- proton    energy spectrum     (GeV^-1 cm^-2 s^-1)
C SPN- neutron   energy spectrum     (GeV^-1 cm^-2 s^-1)
C SPK- pion/kaon energy spectrum     (GeV^-1 cm^-2 s^-1)
C SPM- muon      energy spectrum     (GeV^-1 cm^-2 s^-1)
C SPG- photon    energy spectrum     (GeV^-1 cm^-2 s^-1)
C SPE- e+e-      energy spectrum     (GeV^-1 cm^-2 s^-1)
C
! In any run: Sum_detectors (Sum_types) =< nof_histmax
(=300, default)
```

COMBINING RUNS

Provided all appropriate ways to maximize computing efficiency are already in the given MARS15 model, the method is used with the code in applications requiring very large number of events to get statistical errors on a required level.

Combining Monte Carlo results from several MARS runs starting with different seeds and with (possibly) different number of histories. The sum of scores and the sum of scores squared over all the histories in all the runs allow to calculate the mean and relative error.

Scripts to generate directories with corresponding seeds, submit all the jobs, and – on completion - generate combined MTUPLE files and histograms in **mars.hbook**.

AUTOMATIC GEOMETRY GENERATION

It is a modern approach for accelerator complexes to build a **realistic model of the whole machine** for multi-turn beam loss, energy deposition, activation and radiation shielding studies: read in **MAD lattice** and create a complete geometry and magnetic field model in the MARS.

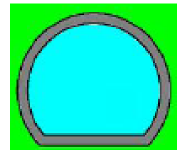
MMBLB = MAD MARS Beam Line Builder

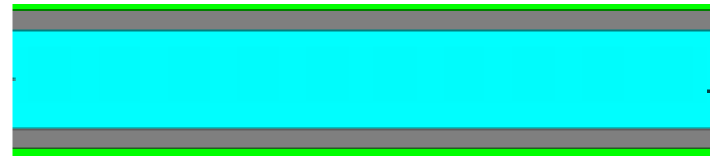
2011: modifications in interface routines of m1510.f for full consistency

MMBLB Approach

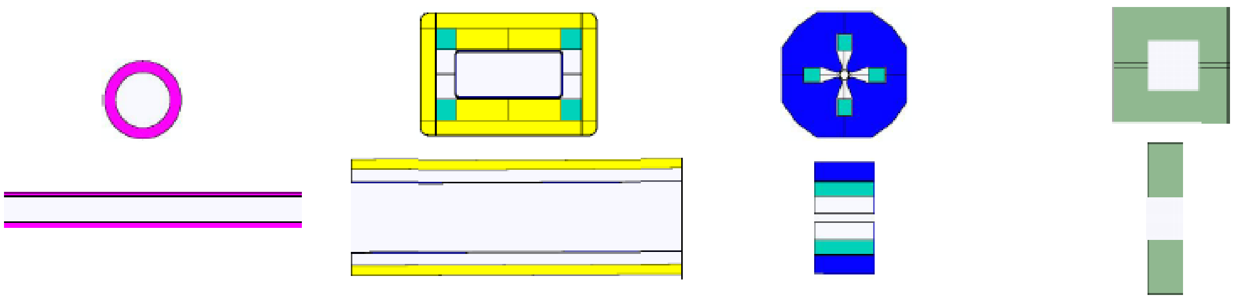
Local coordinate (Definition of each component)

1. Tunnel
2. Beamline component



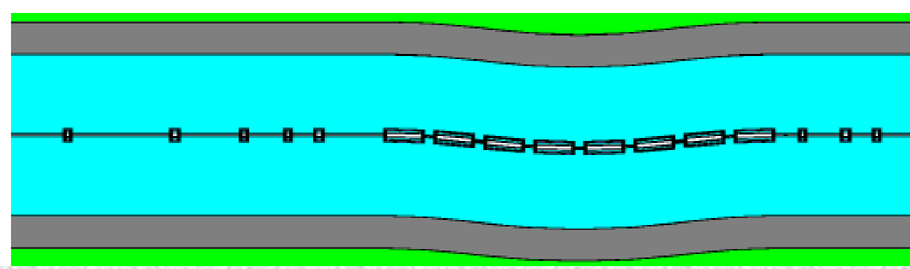


beam pipe, dipole, quadrupole, collimator etc.



Global coordinate (Put components on tunnel)

Location, number, length, bending, magnetic field intensity of components are defined and changed by MAD "OPTICS" file



Compiled by N. Nakao

MMBLB: How to Make It (1)

Subroutines to define each component

- Tunnel
  - Tunnel_geo – geometry
  - Tunnel_mat – material
  - Tunnel_vol – volume (Optional)
  - Tunnel_zonename – name of zone (Optional)

- Beam line component (example: quad)
  - quad_name_func – assign "Type" and "Name" in MAD OPTICS
  - quad_init_func – initialization
  - quad_geo_func – geometry
  - quad_mat_func – material
  - quad_field_func – magnetic field
  - quad_vol_func – volume of zones
  - quad_zonename_func – zone name

Compiled by N. Nakao

MMBLB: How to Make It (2)

- MARS.INP

Declaration of MMBLB

INDX 13=T

Define Vacuum in mother volume

ZSEC 5000. 2501=0 (when 2=T)

RSEC 1000. 101=0 (when 2=T)

- m1507.f (subroutines to be modified)

uncomment related sentence for these subroutines

```
*      IF (IND(13)) THEN
       :
*      ENDIF
```

reg1 – define M_MAX   PARAMETER (M_MAX= beamline_nof_zones + tunnel_nof_zones)

field

blinit – define initial condition

blgeoinit – registration of all subroutines of beamline components

Compiled by N. Nakao

MMBLB: How to Make It (3)

MAD optics file

"Keyword"	"Type"	"Name"	SumL	L [m]	Bend k0 [m]	Q k1 [rad]	Sx k2	Oc k3	Tilt [rad]
"DRIFT"	"DL10"	"DPCBPM"	1.0	1.0	0.	0.	0.	0.	0.
"SBEND"	"H20"	"BPC1"	4.0	3.0	2.4E-4	0.	0.	0.	0.
"DRIFT"	"DL10"	"DPCBBO"	20.0	16.0	0.	0.	0.	0.	0.
"SBEND"	"H20“	"BPC1"	23.0	3.0	2.4E-4	0.	0.	0.	0.
"DRIFT"	"DL10"	"DPCBBO"	20.5	16.0	0.	0.	0.	0.	0.

Specific MAD keywords (15) are allowed

Type defined in name_func

Ignored

Ignored

Element length

Bend angle

Gradient factors magnetic field

Roll angle

Compiled by N. Nakao

MMBLB: How to Make It (4)

Main "Keyword" in OPTICS

"DRIFT"

"SBEND"

"RBEND"

"QUADRUPOLE"

"SEXTUPOLE"

"OCTUPOLE"

"ECOLLIMATOR"

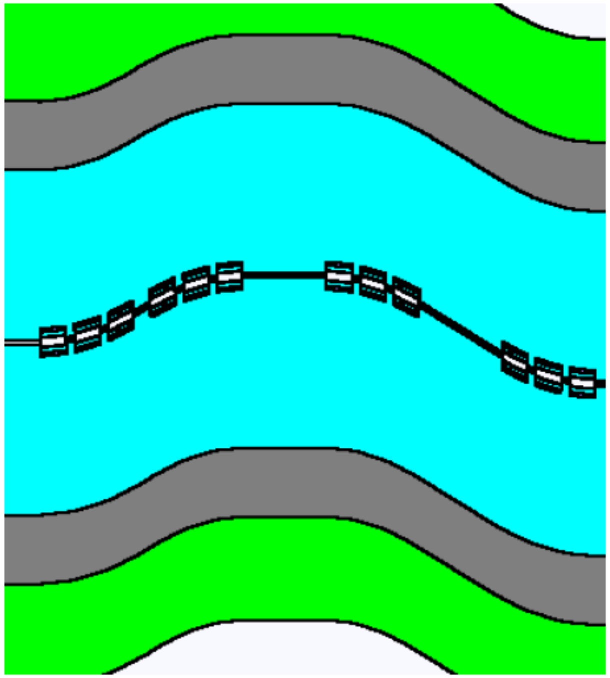
"RCOLLIMATOR"

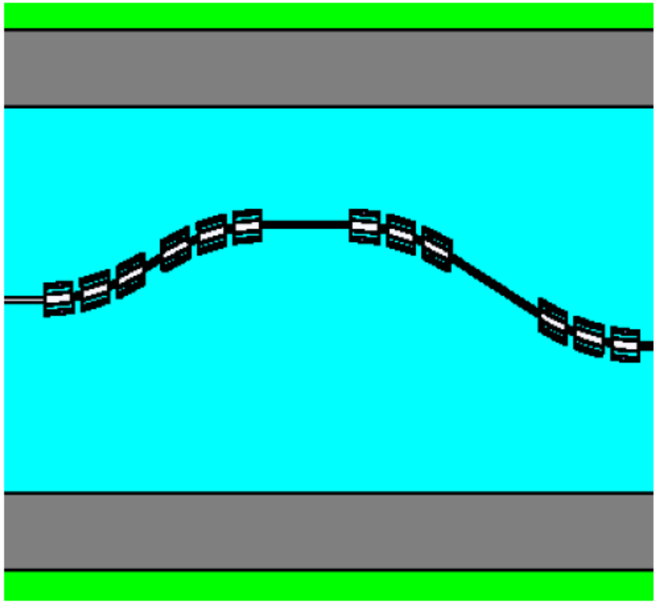
etc.

Compiled by N. Nakao

MMBLB: How to Make It (5)

Subroutine Tunnel_geo





* Local beam line coordinates

x=xlocmad

y=ylocmad

z=zlocmad

Tunnel follows beam line shape

* Global MARS coordinates

x=xglmad

y=yglmad

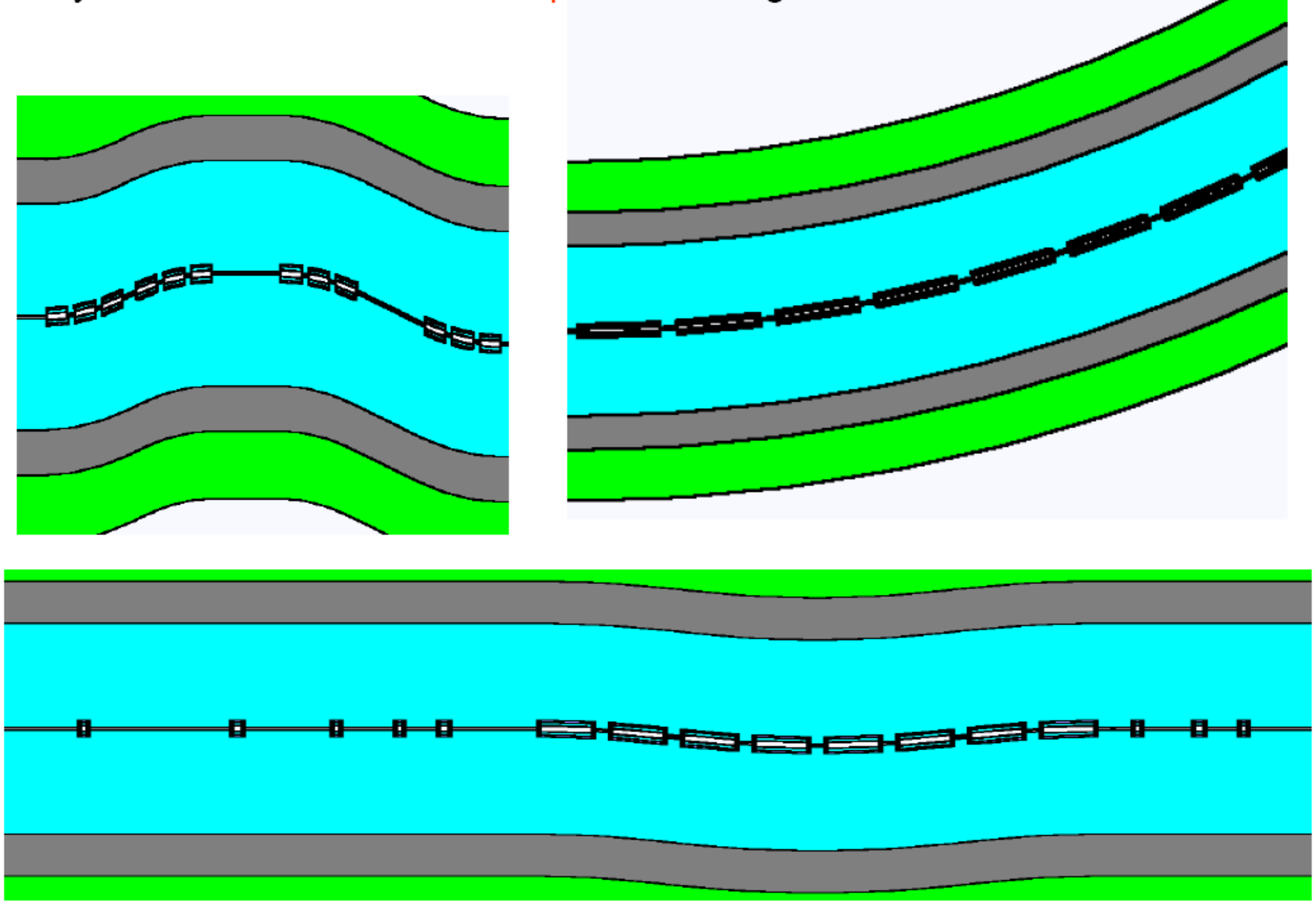
z=zglmad

Tunnel is independent of beam line shape

Compiled by N. Nakao

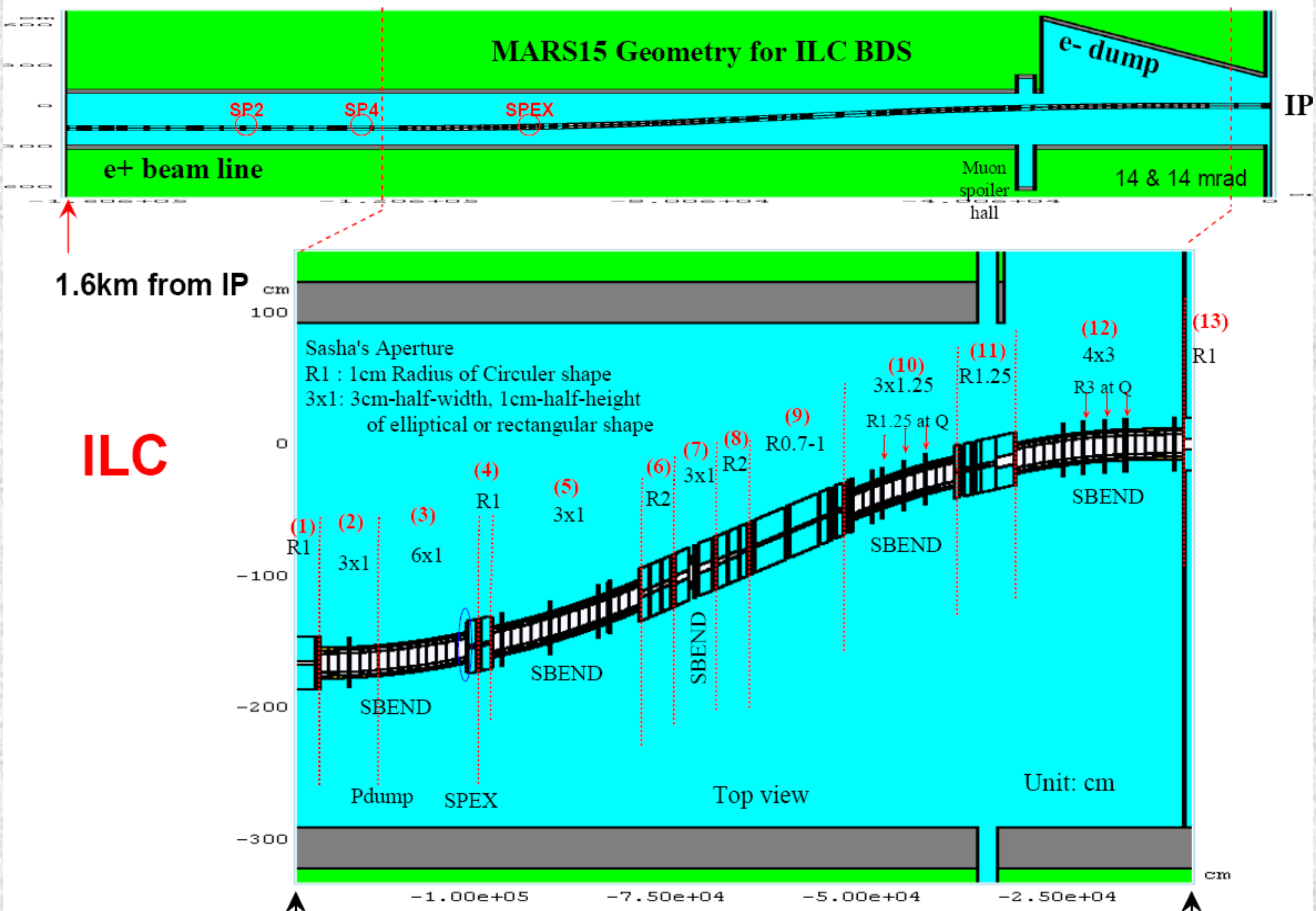
MMBLB: How to Make It (6)

Variety beam lines with same components using different OPTICS



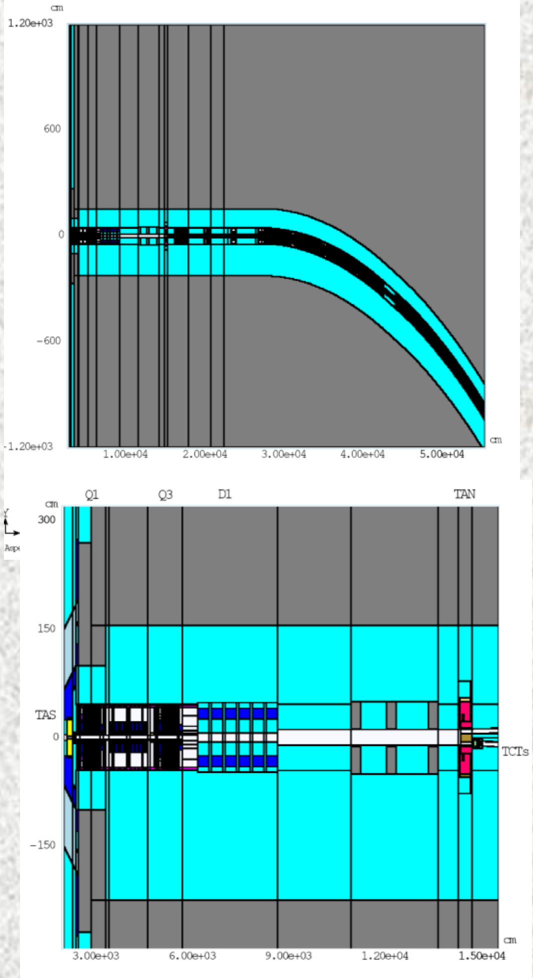
Compiled by N. Nakao

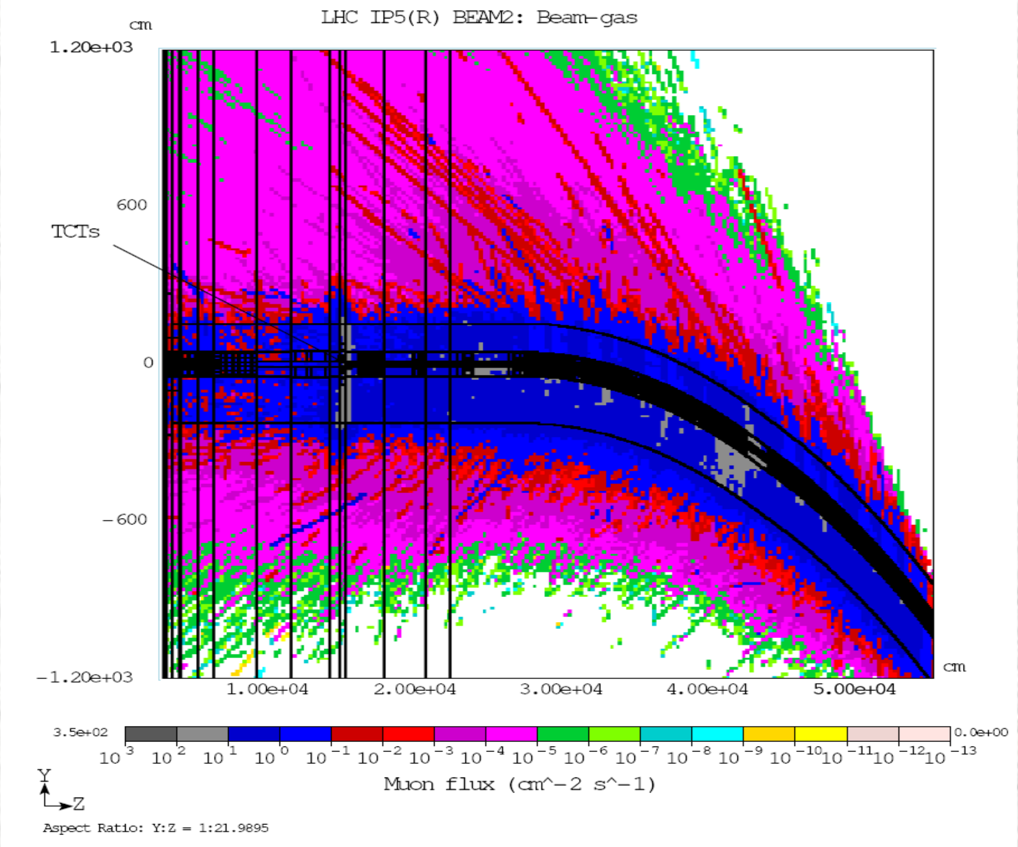
MMBLB: How to Make It (7)



Compiled by N. Nakao

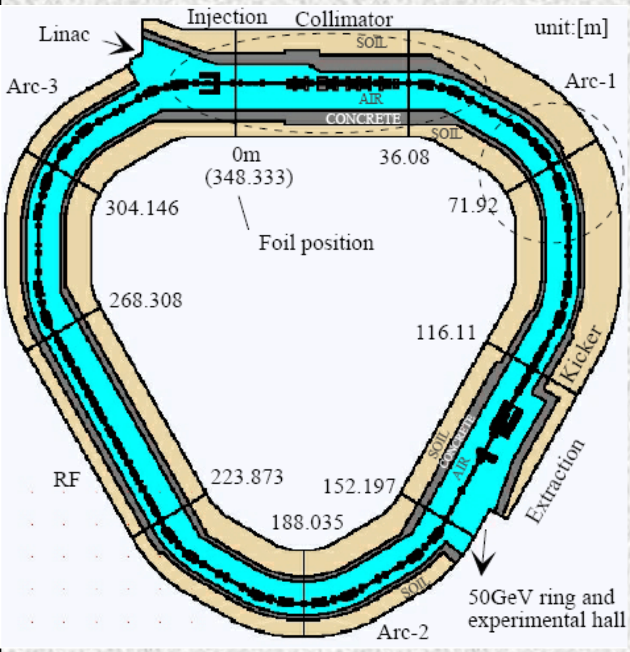
MMBLB for 500-m LHC IP5

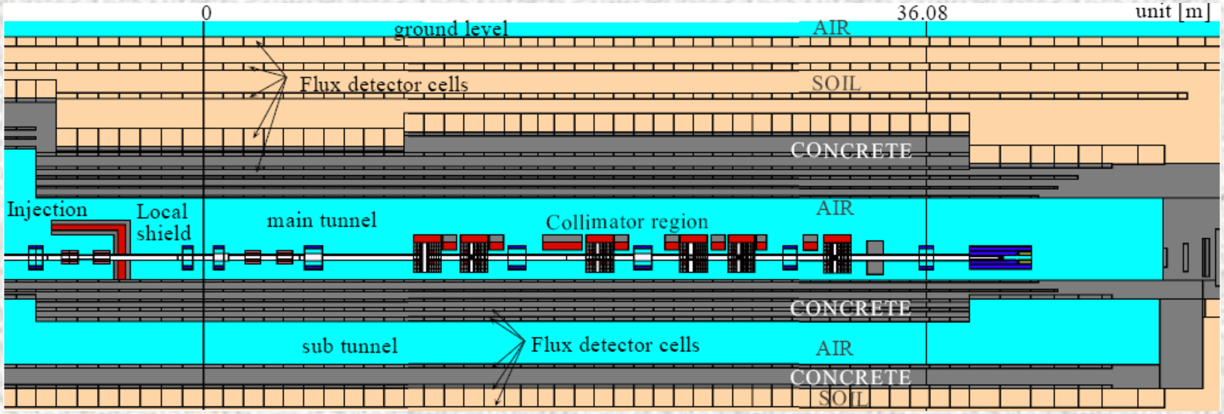


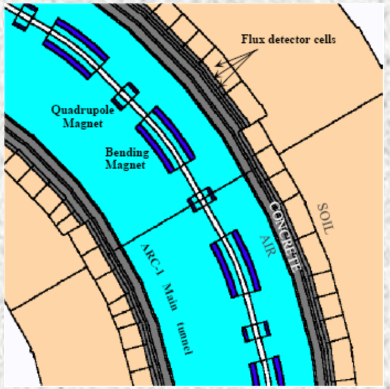


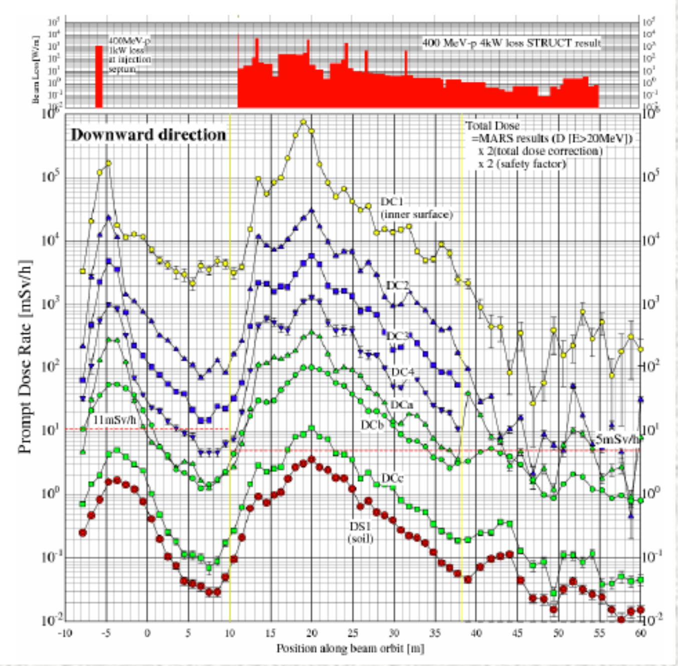
Kilometers of magnetic structure with detailed 3D geometry in Tevatron, LHC and ILC; entire ring description for J-PARC and Fermilab Booster

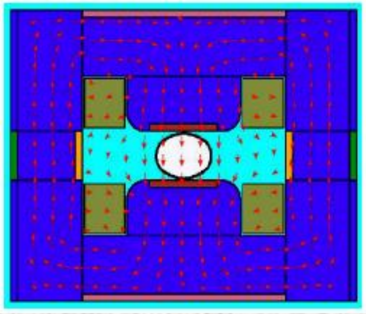
MAD-MARS BEAM LINE BUILDER: J-PARC 3-GeV RING

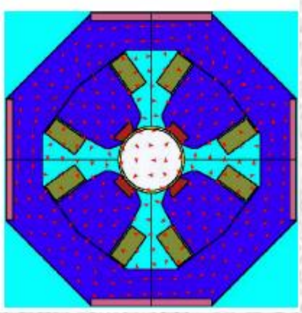












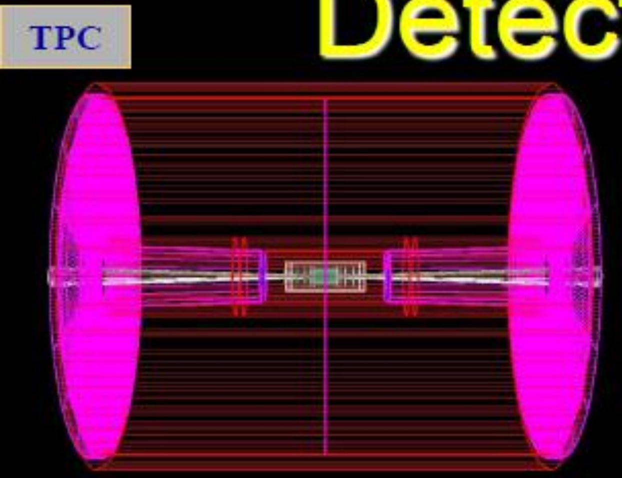
By N. Nakao

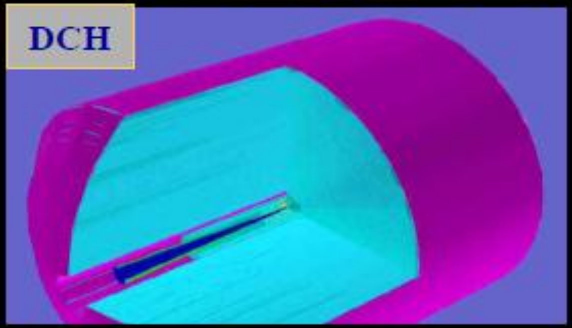
MARS + ILCroot (Oct. 2009)

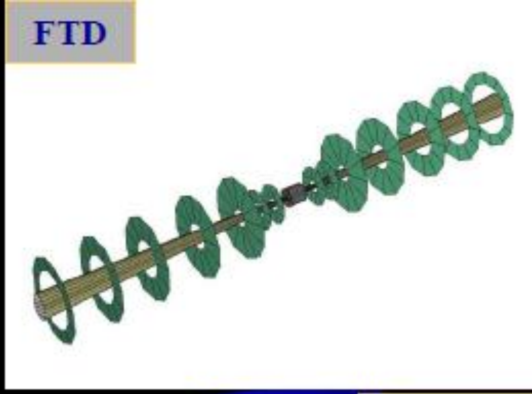
- The ingredients:
  - Final Focus descripted in MARS & ILCroot
  - Detector description in ILCroot
  - MARS-to-ILCroot interface (Vito Di Benedetto)

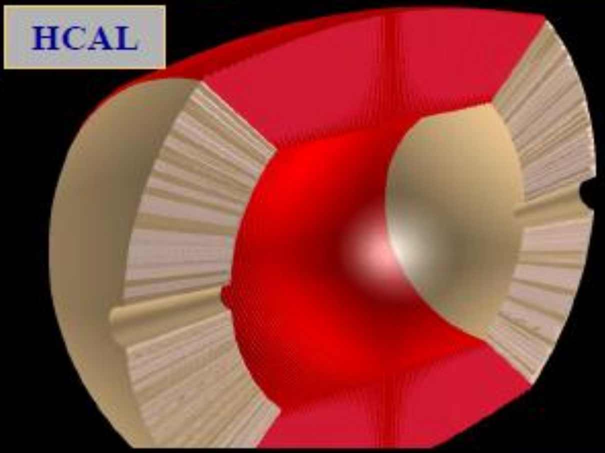
- How it works
  - The interface (ILCGenReaderMARS) is a *TGenerator* in ILCroot
  - MARS output is used as a config file
  - ILCGenReaderMARS create a STDHEP file with a list of particles entering the detector area at z = 7.5m
  - MARS weights are used to generate the particle multiplicity for G4
  - Threshold cuts are specified in Config.C to limit the particle list fed to G4
  - Geant4 takes over at 7.5m
  - Events are finally passed through the usual simulation (G4)-> digitization->reconstruction machinery

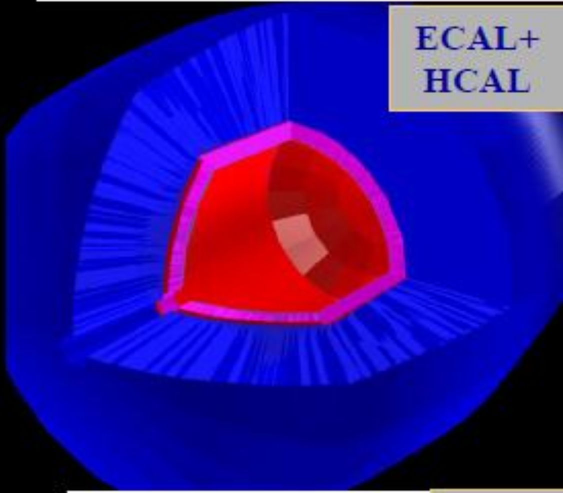
Detectors in ILCroot

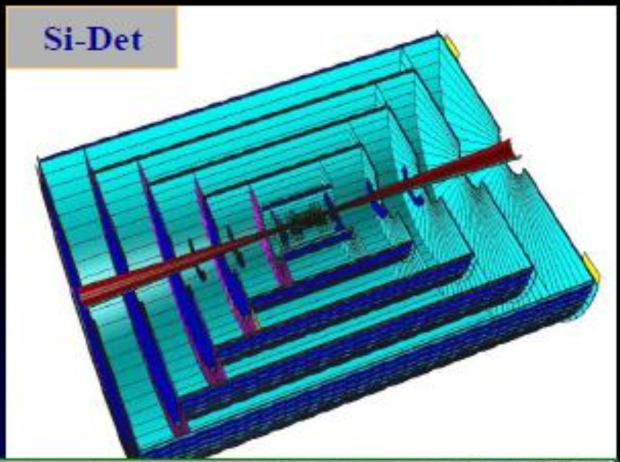


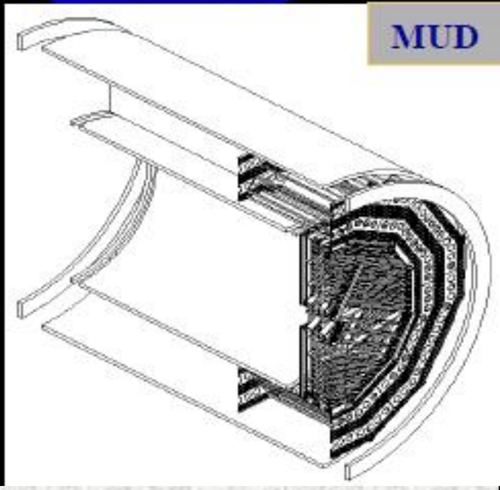


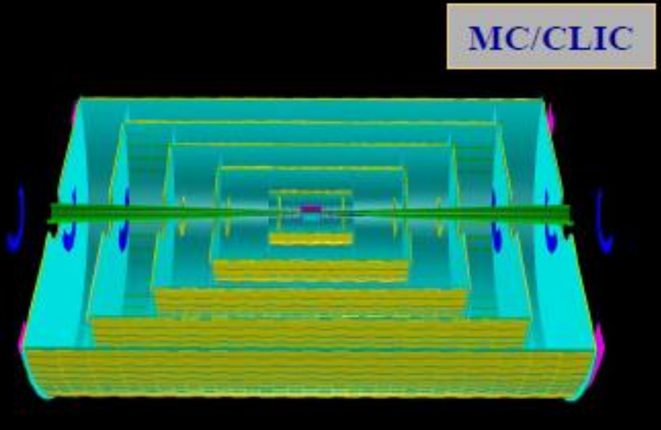


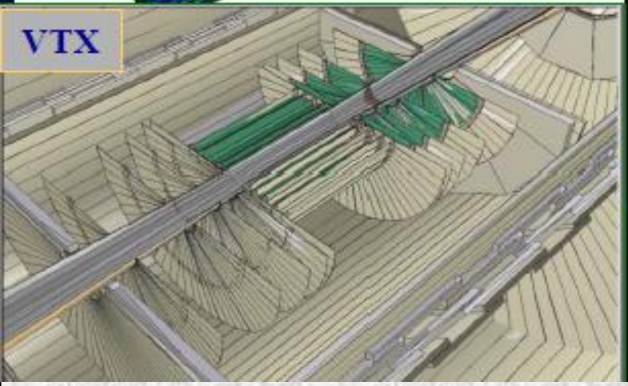






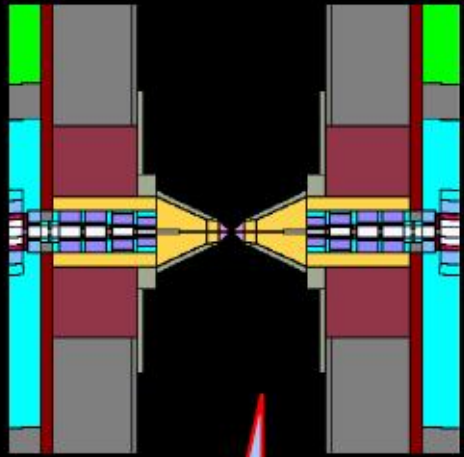




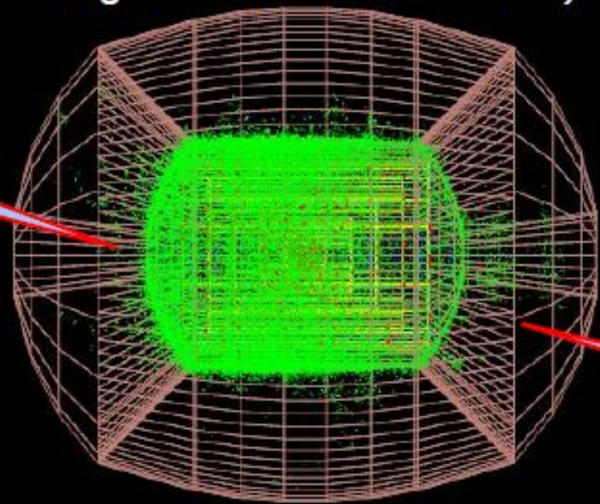


Detector Response Study with MARS+ ILCroot

- MARS background provided at the surface of MDI (10° nozzle + walls)



- GEANT4 or fluka simulated particles in the detector
  (background + single muons from the I.P.)



- Reconstructed tracks from a parallel Kalman Filter in a 3.5 T B-field
- Reconstructed energy towers from a Dual Readout calorimeter

MARS15 Applications at Colliders

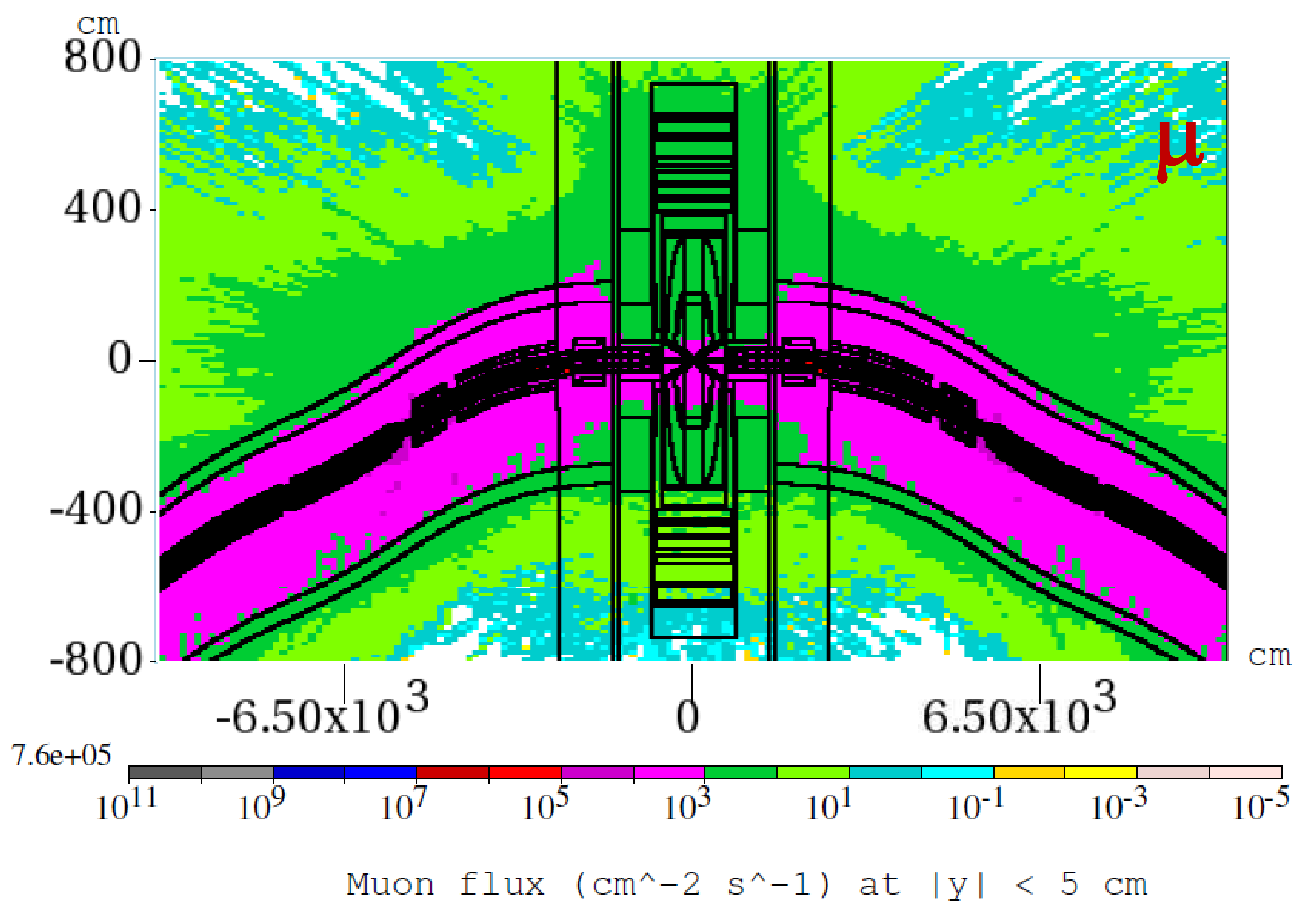
- **Tevatron** complex (since 1979): beam abort and beam collimation systems; backgrounds & MDI for the CDF and D0 collider detectors; Linac/Booster/Main_Injector chain; beam instrumentation; numerous radiation problems; fixed target experiments: neutrino (NuMI/MINOS, NoVA, MiniBoone, DONUT, LBNE), mu2e, g-2, kaons, SeaQuest etc.

- **LHC** (since 1993): beam abort and collimation systems; full responsibility for machine-induced backgrounds in CMS (and partially in ATLAS); forward-physics experiments, fusion with hydrodynamics; upgrade scenarios etc.

- **Muon collider and Neutrino Factory** (since 1994): targetry, machine-detector interface, machine protection, neutrino-induced hazard etc.

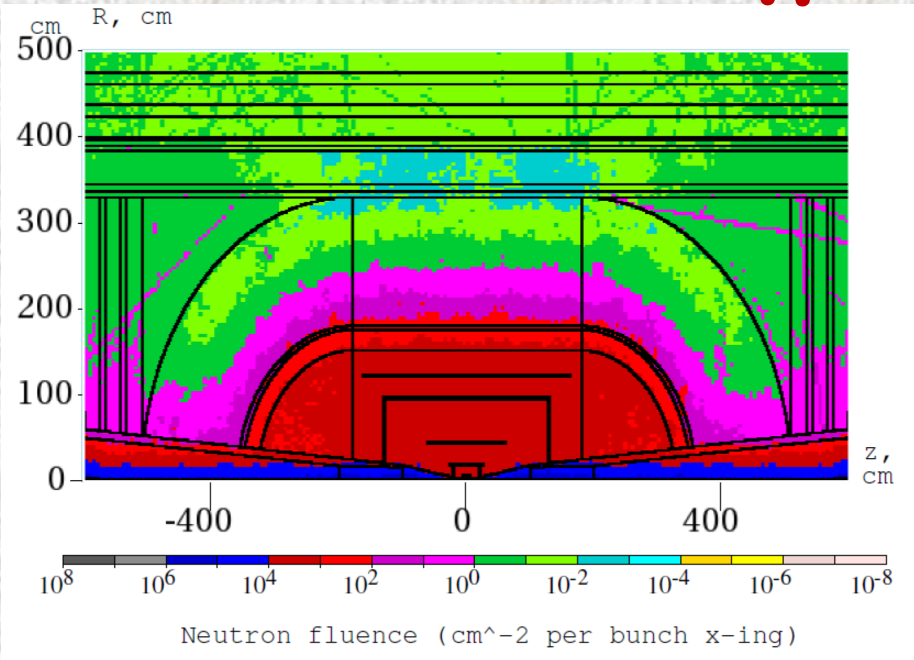
- **VLHC and ILC**

Muon Collider

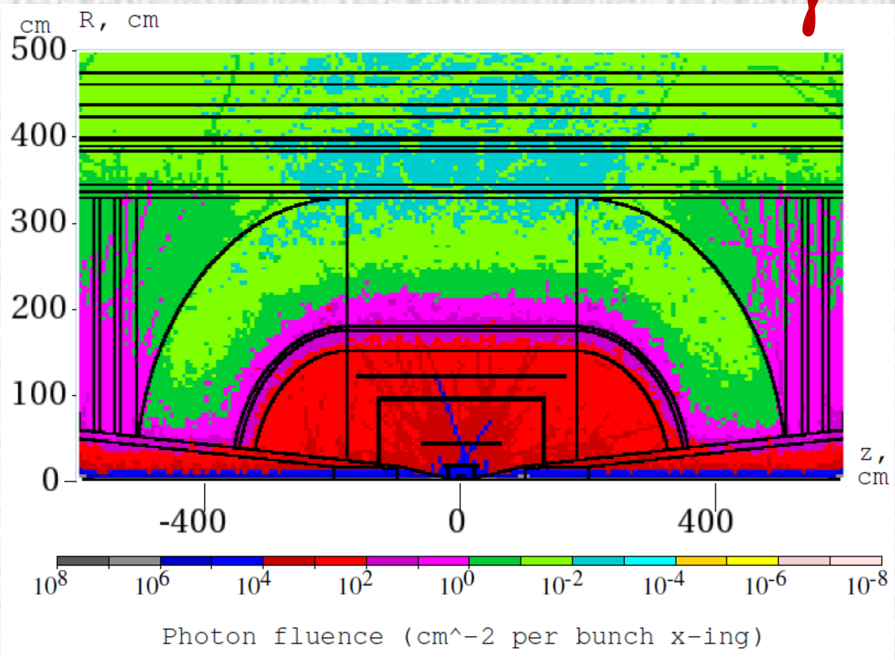


Muon Collider: Neutron and Photon Fluence

n

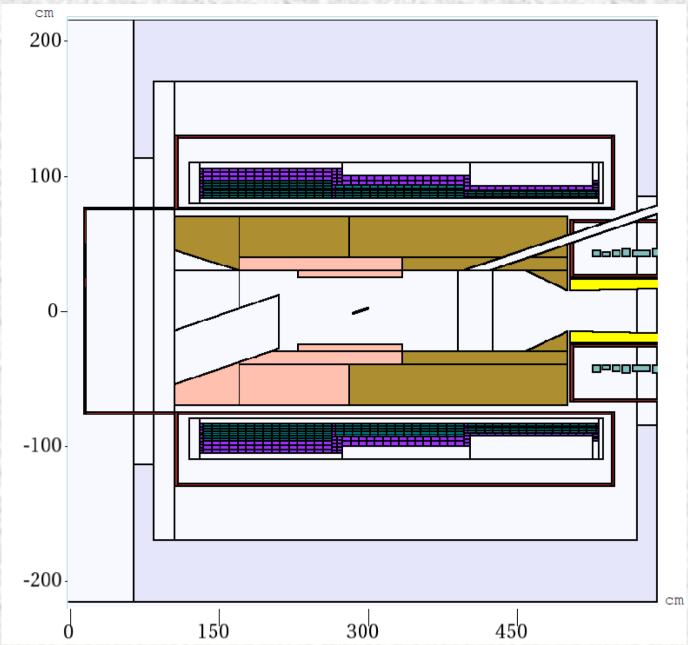


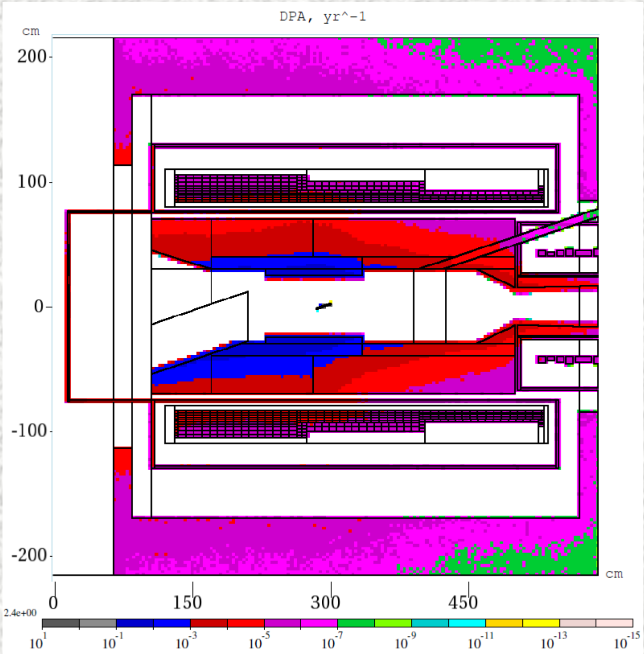
γ

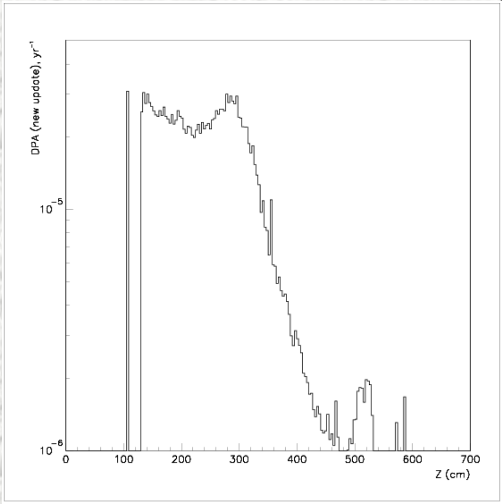


Maximum neutron fluence and absorbed dose in the innermost layer of the silicon tracker for a one-year operation are at a 10% level of that in the LHC detectors at the luminosity of 10^{34} $cm^{-2}s^{-1}$

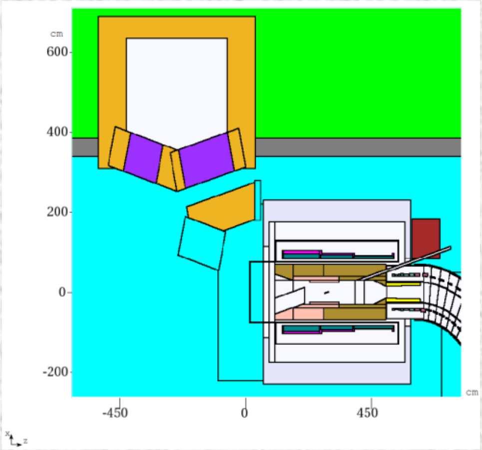
Mu2e Production Solenoid

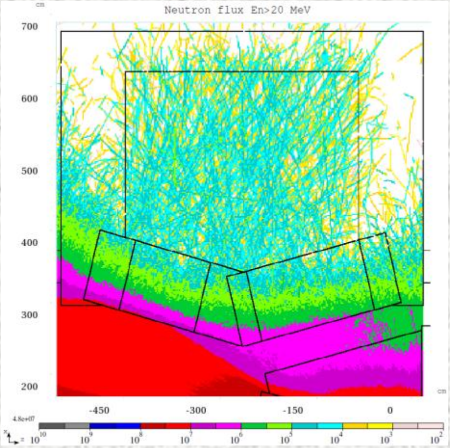






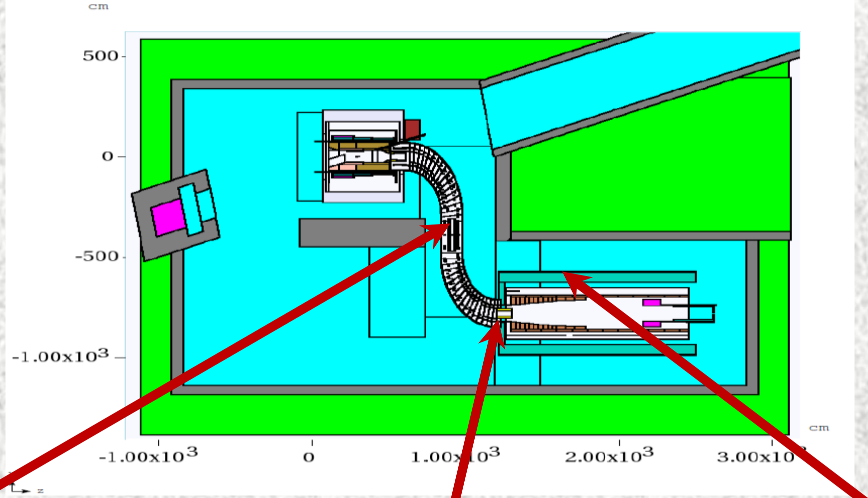
Minimizing radiation damage to superconducting coils





Hot cell design

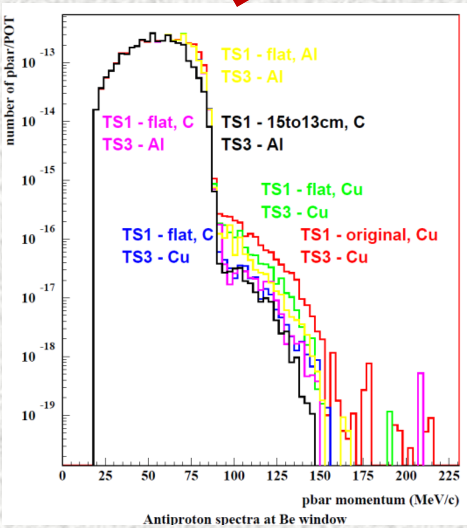
Mu2e: Dealing with Backgrounds

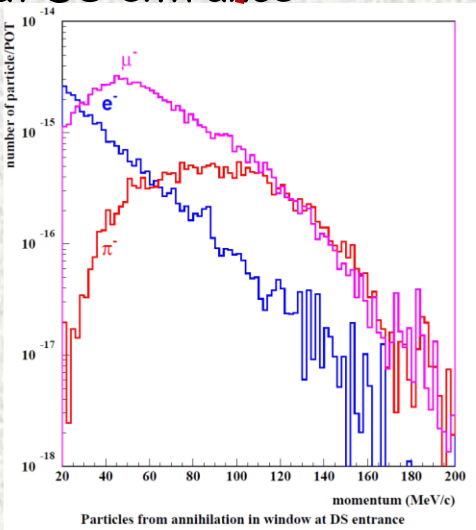


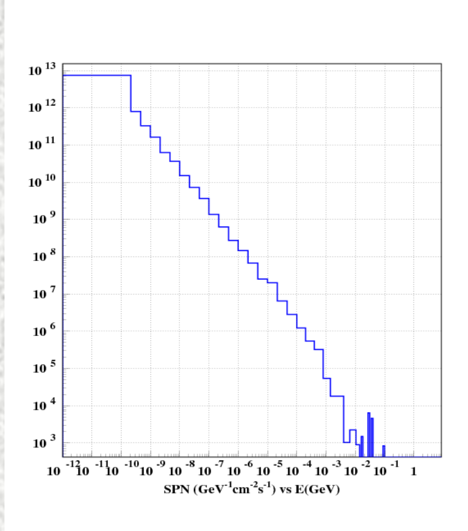
Pbar spectra at collimator Be window

Pbar-induced spectra at DS entrance

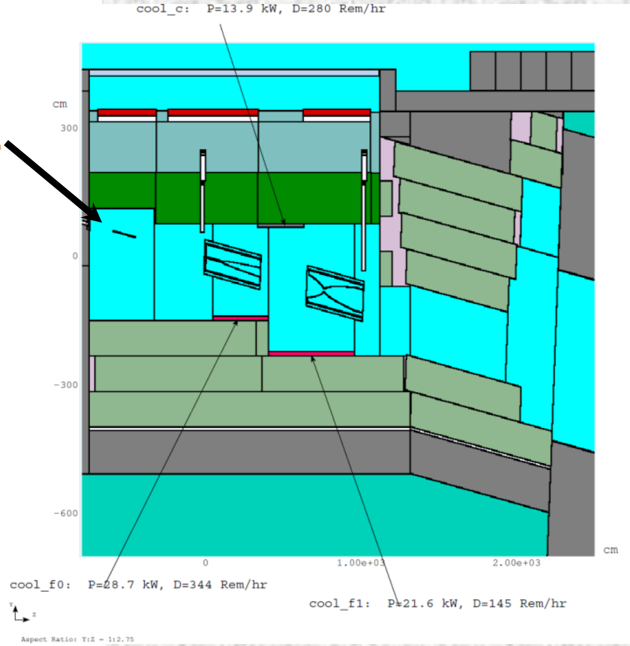
Neutron spectrum on cosmic ray veto counter

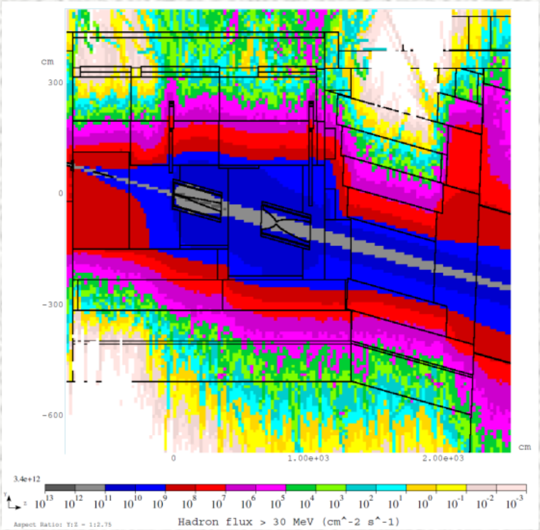




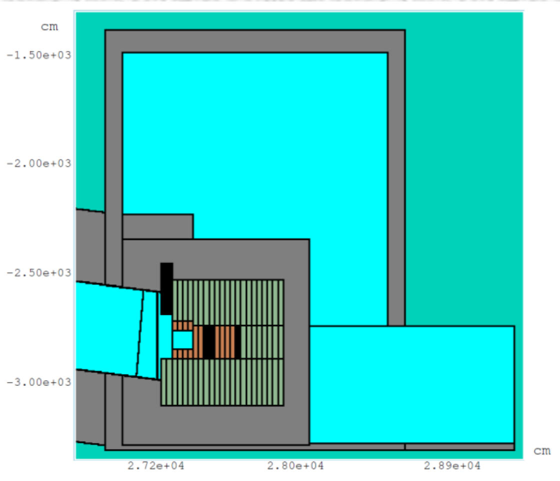


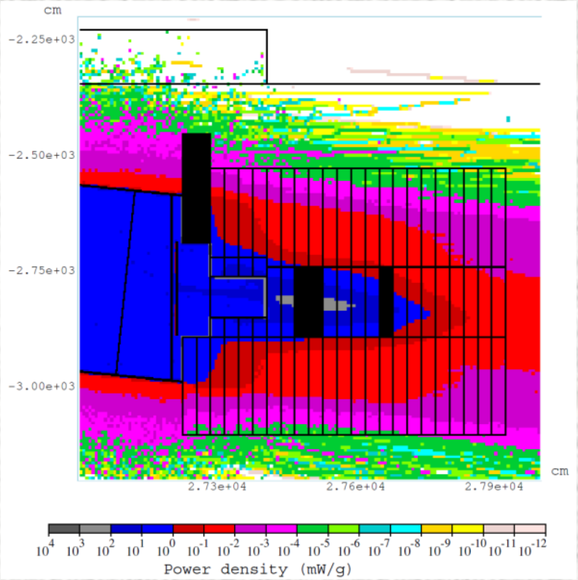
LBNE: Primary Beamline & Target Station

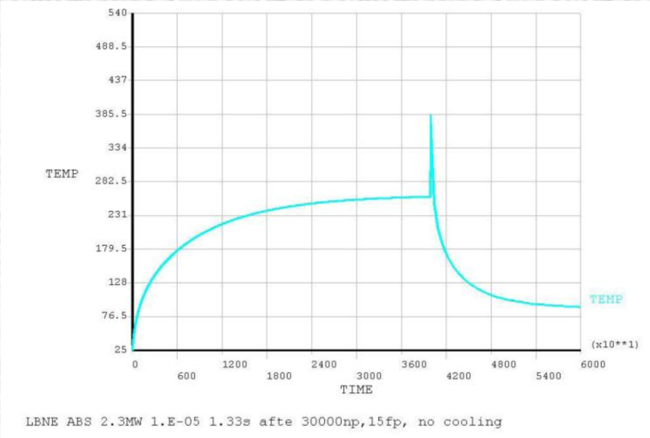




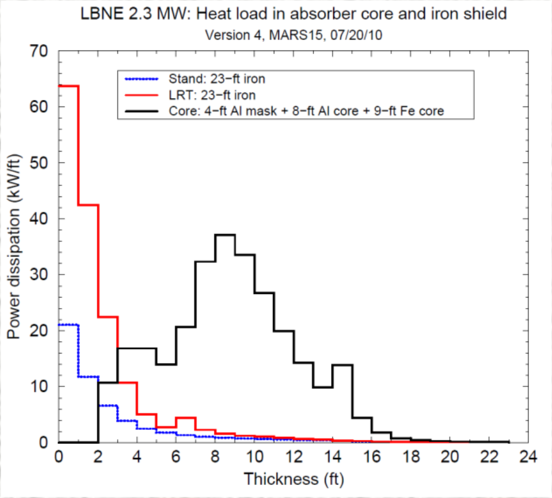
LBNE: Dynamic Heat Loads, Shielding and ND

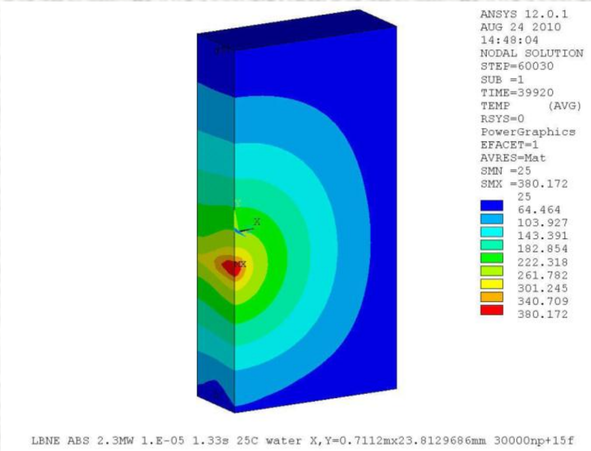


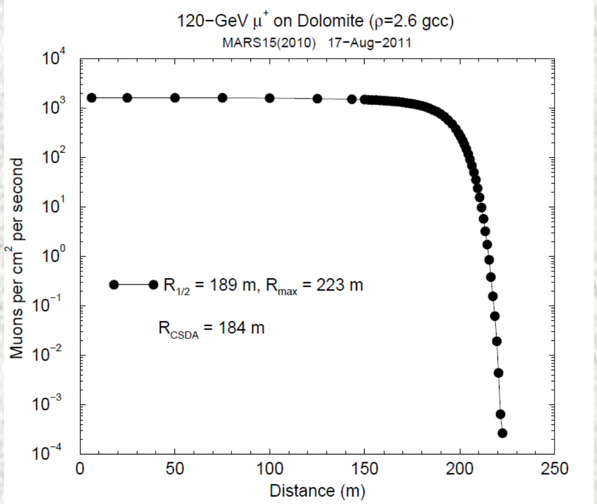




Minimal distance to Near Detector

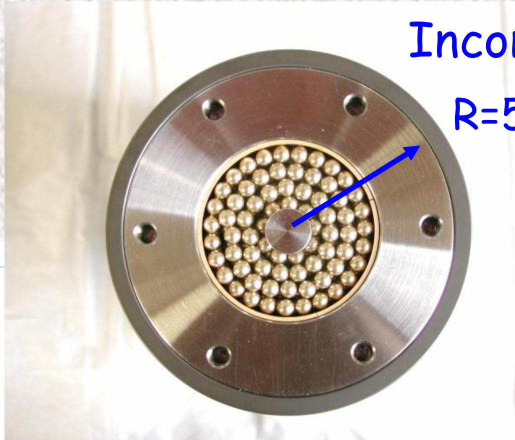


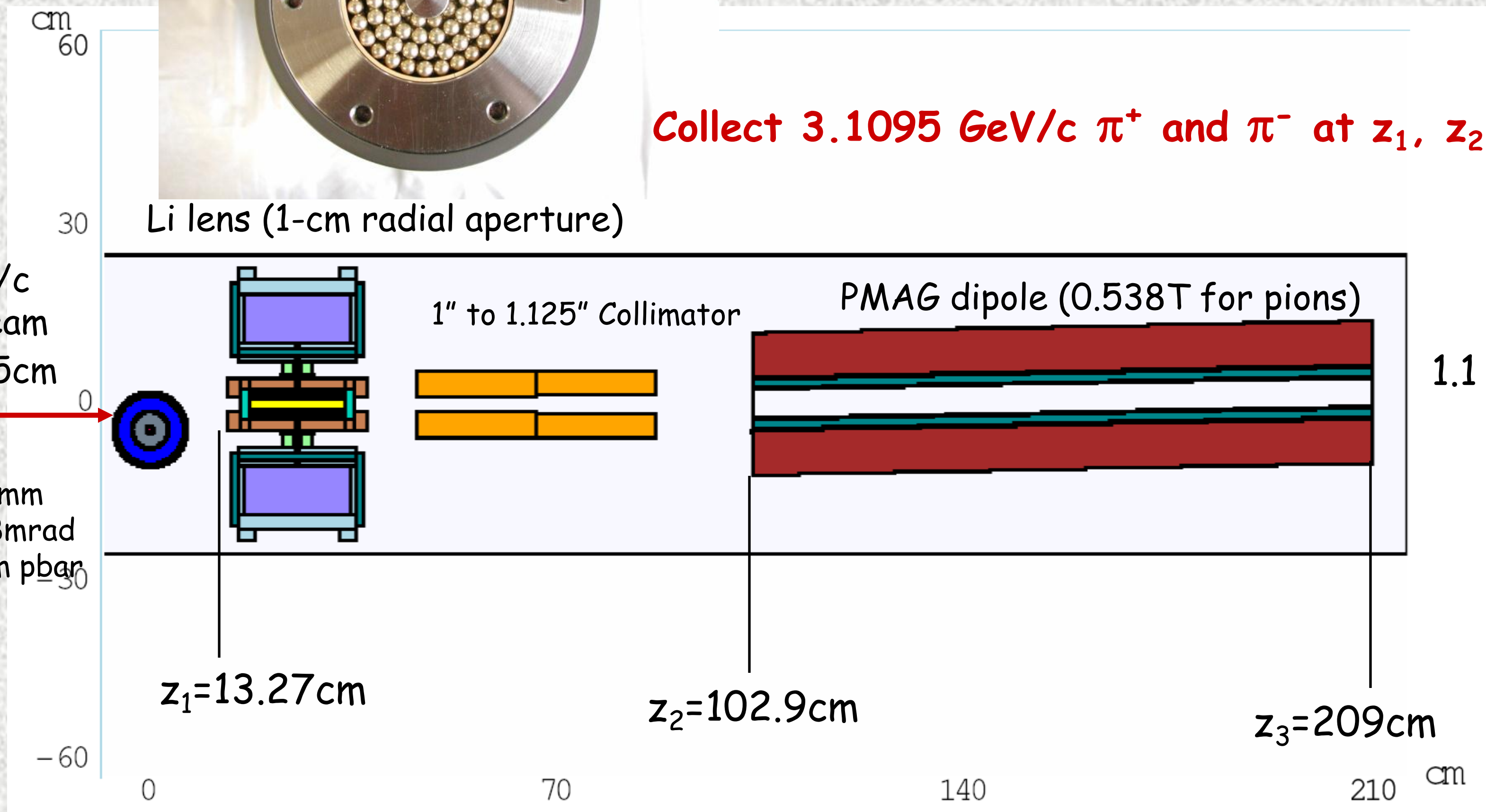




MARS15 MODEL OF PBAR TARGET SETUP

The fields/currents scaled from pbar operation by factor of 3.1095/8.89





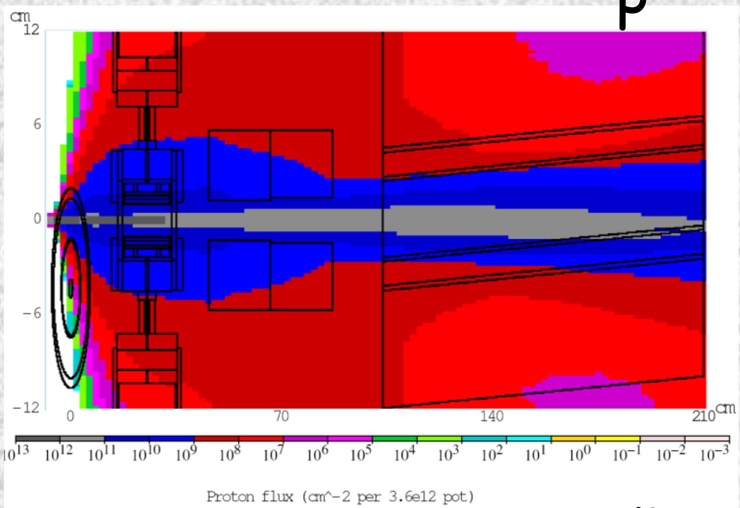
8.89 GeV/c proton beam
Chord=7.5cm

$\sigma_x=\sigma_y$=0.55mm
$\sigma_{x'}=\sigma_{y'}$=0.38mrad
scaled from pbar operation

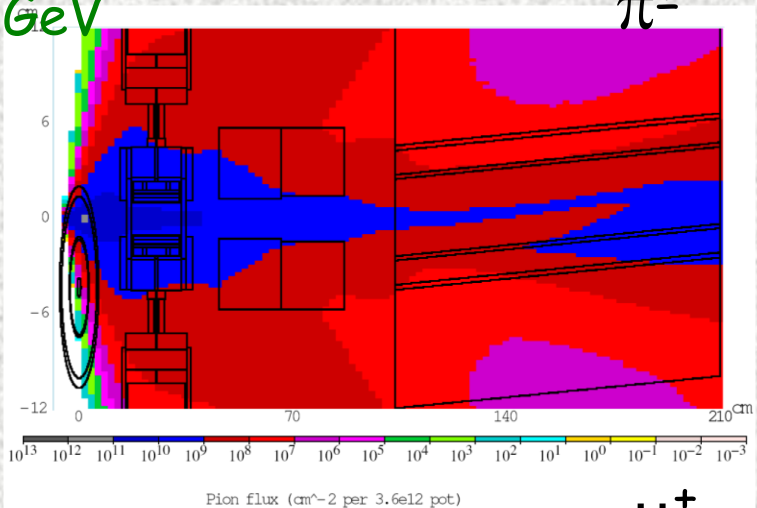
PARTICLE FLUX ISOCONTOURS: π^- mode

p

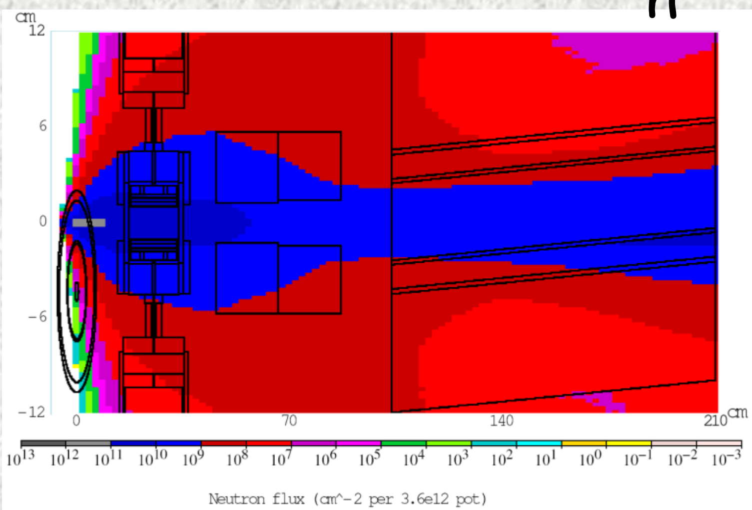
$E_{kin} > 1.5$ GeV



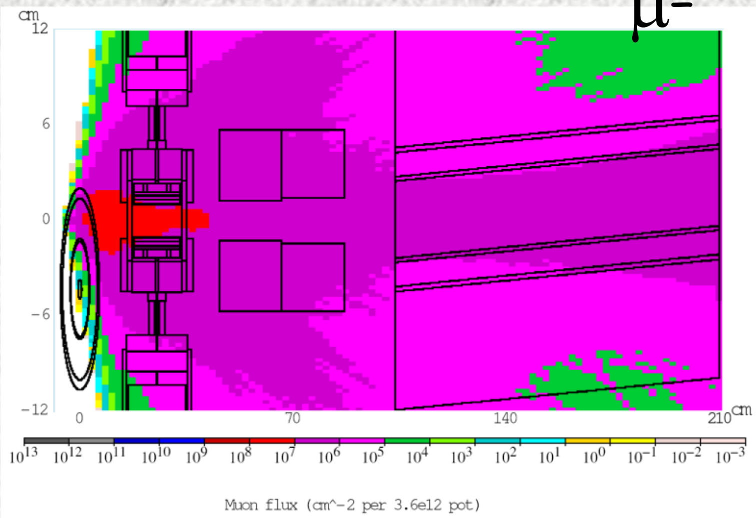
$\pi^{\pm}$



n



$\mu^{\pm}$



In PMAG aperture: 1.5e-5 π^-/pot at 3.1095 ± 1% GeV/c